US010056425B2

# (12) United States Patent
Cao et al.

(10) Patent No.: US 10,056,425 B2
(45) Date of Patent: Aug. 21, 2018

(54) **METHODS OF MAKING SEMICONDUCTOR X-RAY DETECTOR**

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( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/309,059**

(22) PCT Filed: **Jul. 9, 2015**

(86) PCT No.: **PCT/CN2015/083636**
§ 371 (c)(1),
(2) Date: **Nov. 4, 2016**

(87) PCT Pub. No.: **WO2017/004824**
PCT Pub. Date: **Jan. 12, 2017**

(65) **Prior Publication Data**

US 2018/0108702 A1 Apr. 19, 2018

(51) **Int. Cl.**
***H01L 27/146*** (2006.01)
***H01L 31/115*** (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC .... ***H01L 27/14661*** (2013.01); ***H01L 27/1469*** (2013.01); ***H01L 27/14636*** (2013.01); ***H01L 27/14659*** (2013.01); ***H01L 27/14694*** (2013.01); ***H01L 31/02005*** (2013.01); ***H01L 31/022408*** (2013.01); ***H01L 31/0304*** (2013.01); ***H01L 31/115*** (2013.01); ***H01L 31/184*** (2013.01); ***H01L 31/1892*** (2013.01); ***H02S 40/44*** (2014.12); *G01T 1/24* (2013.01); *H01L 31/09* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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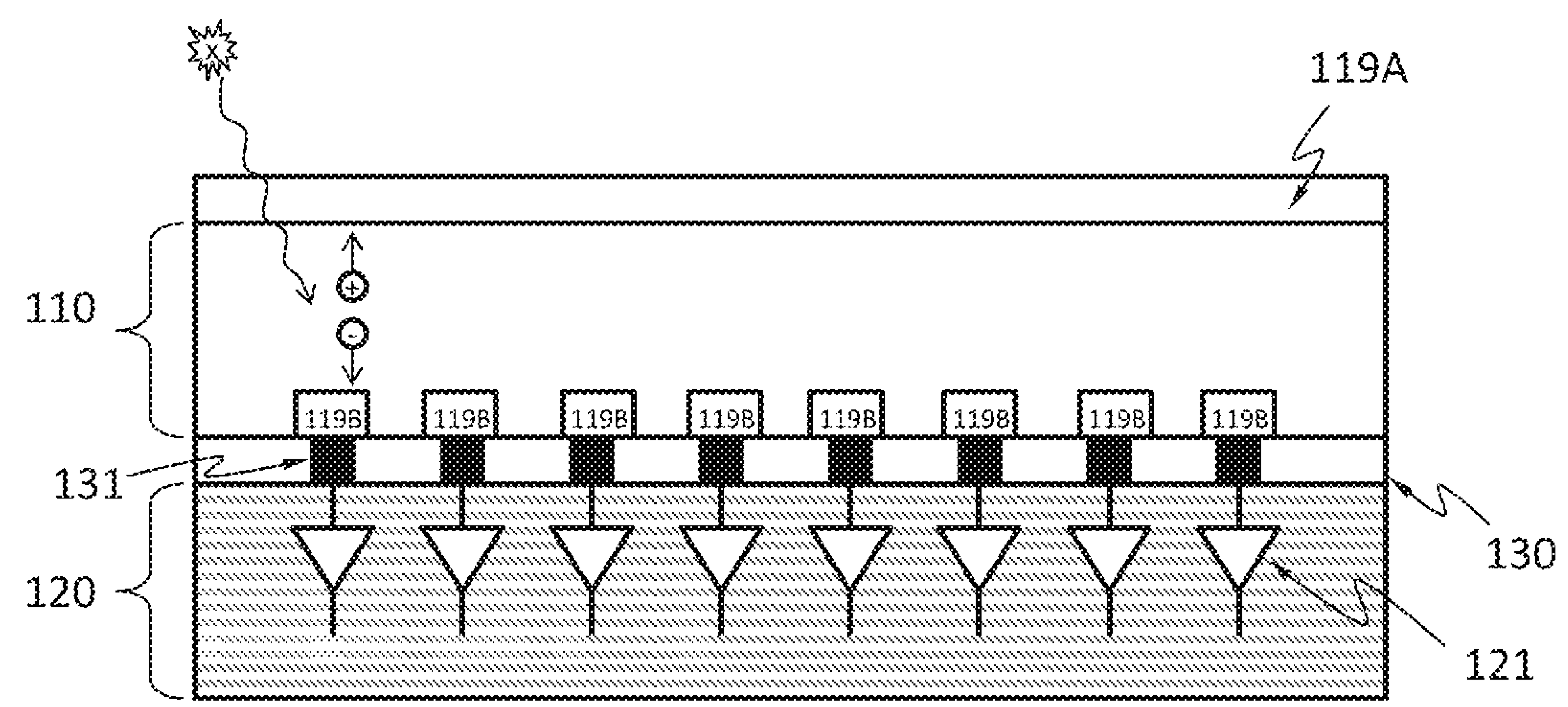
(57) **ABSTRACT**

Disclosed herein is a method of making an apparatus suitable for detecting x-ray, the method comprising: attaching a chip comprising an X-ray absorption layer to a surface of a substrate, wherein the surface is electrically conductive; thinning the chip; forming an electrical contact in the chip; bonding an electronic layer to the chip such that the electrical contact of the chip is electrically connected to an electrical contact of the electronic layer.

**23 Claims, 27 Drawing Sheets**



(51) **Int. Cl.**

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| ***H01L 31/02*** | (2006.01) |
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| ***H01L 31/0304*** | (2006.01) |
| ***H01L 31/18*** | (2006.01) |
| ***H02S 40/44*** | (2014.01) |
| *H01L 31/09* | (2006.01) |
| *G01T 1/24* | (2006.01) |


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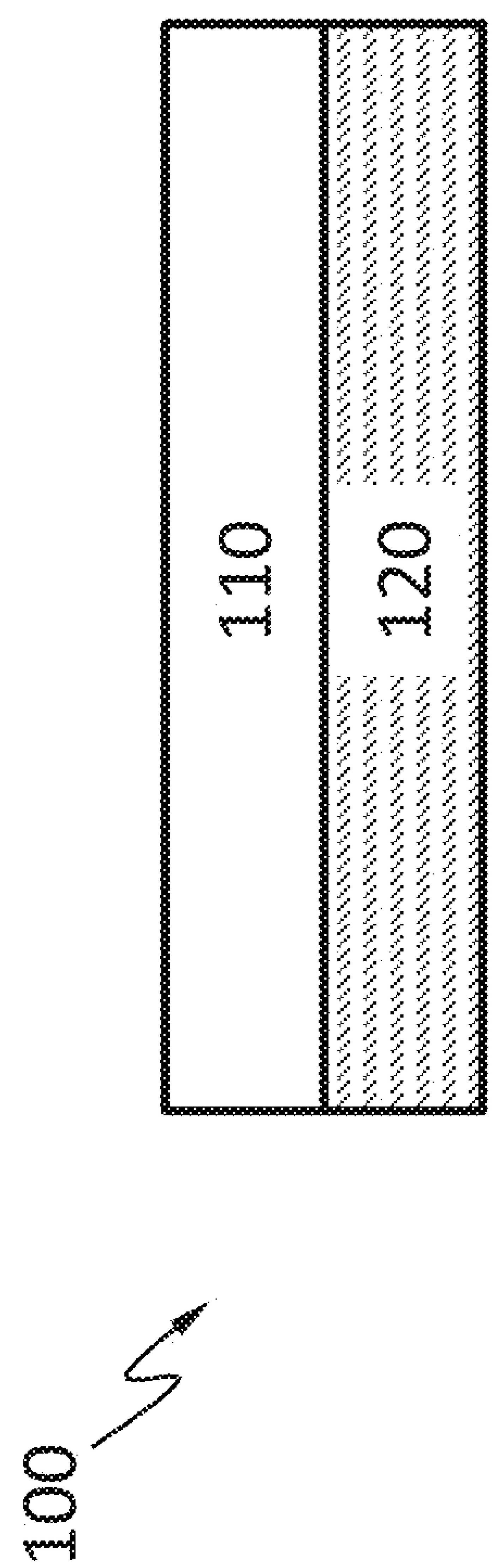



Fig. 1A

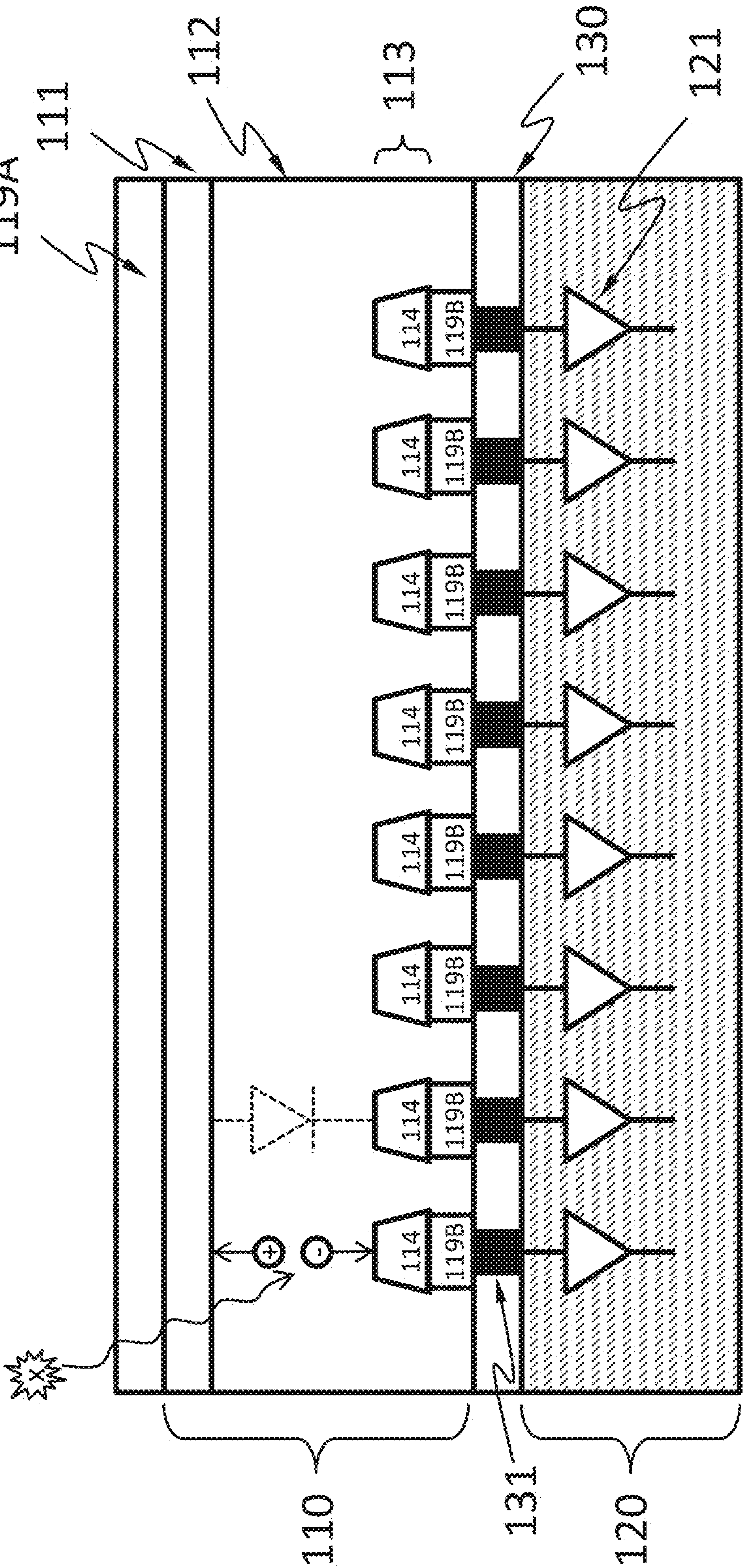



Fig. 1B

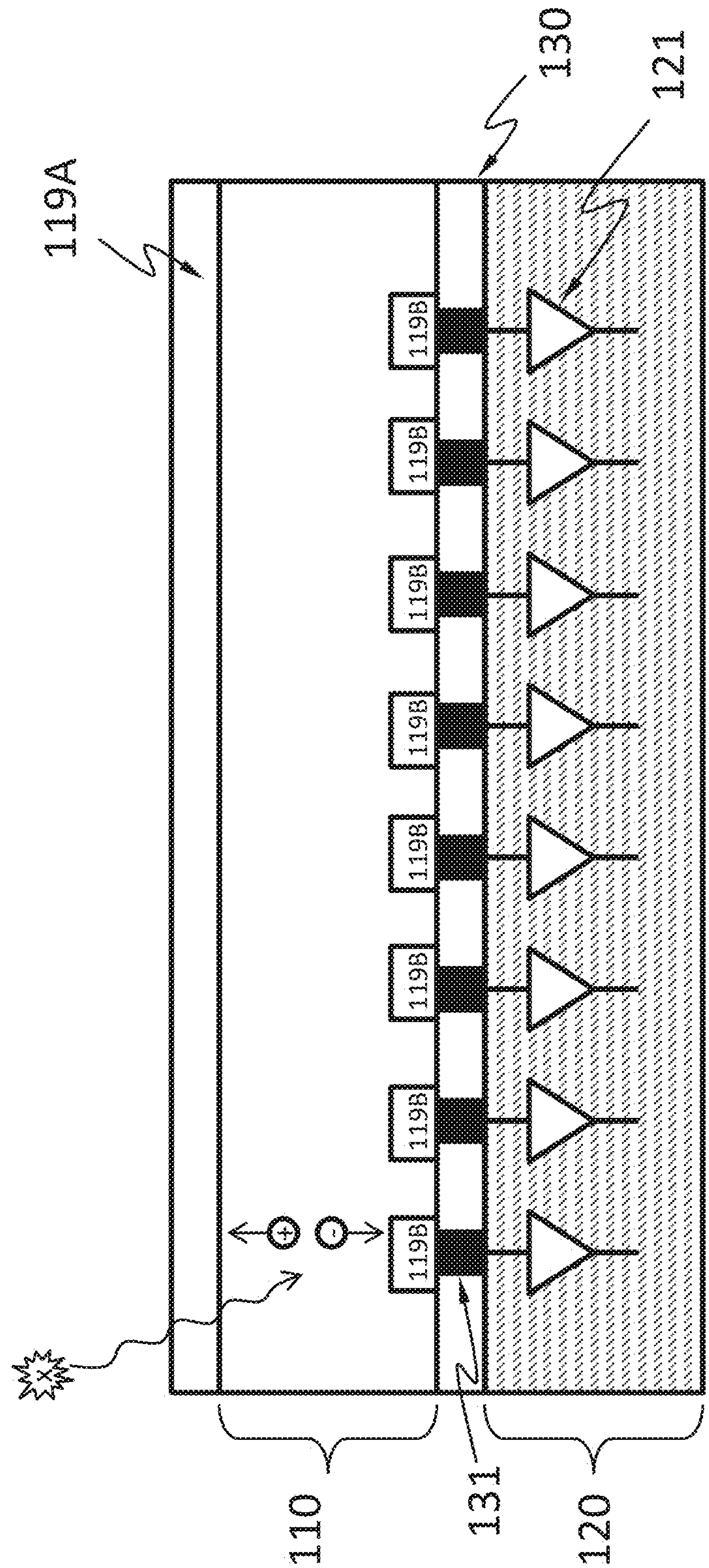



Fig. 1C

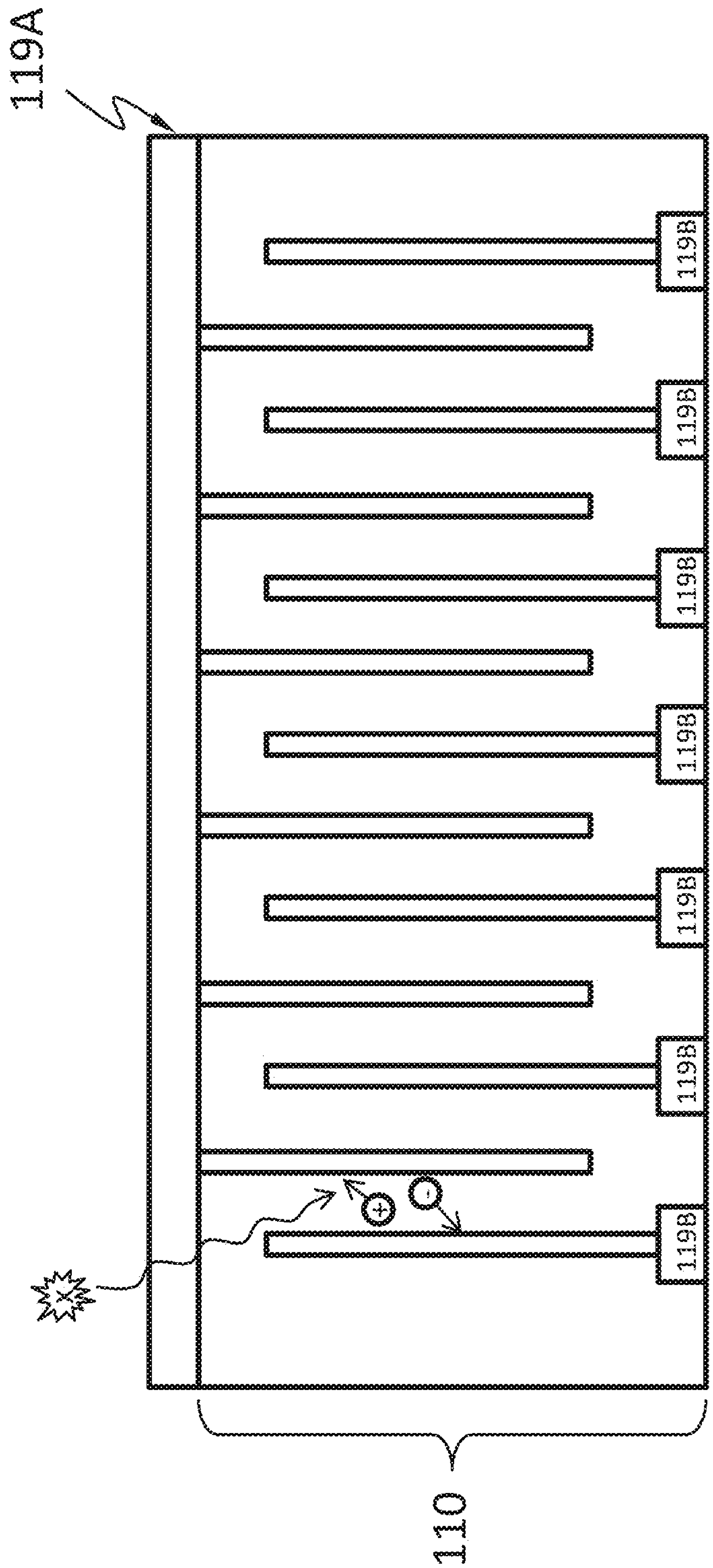



Fig. 1D

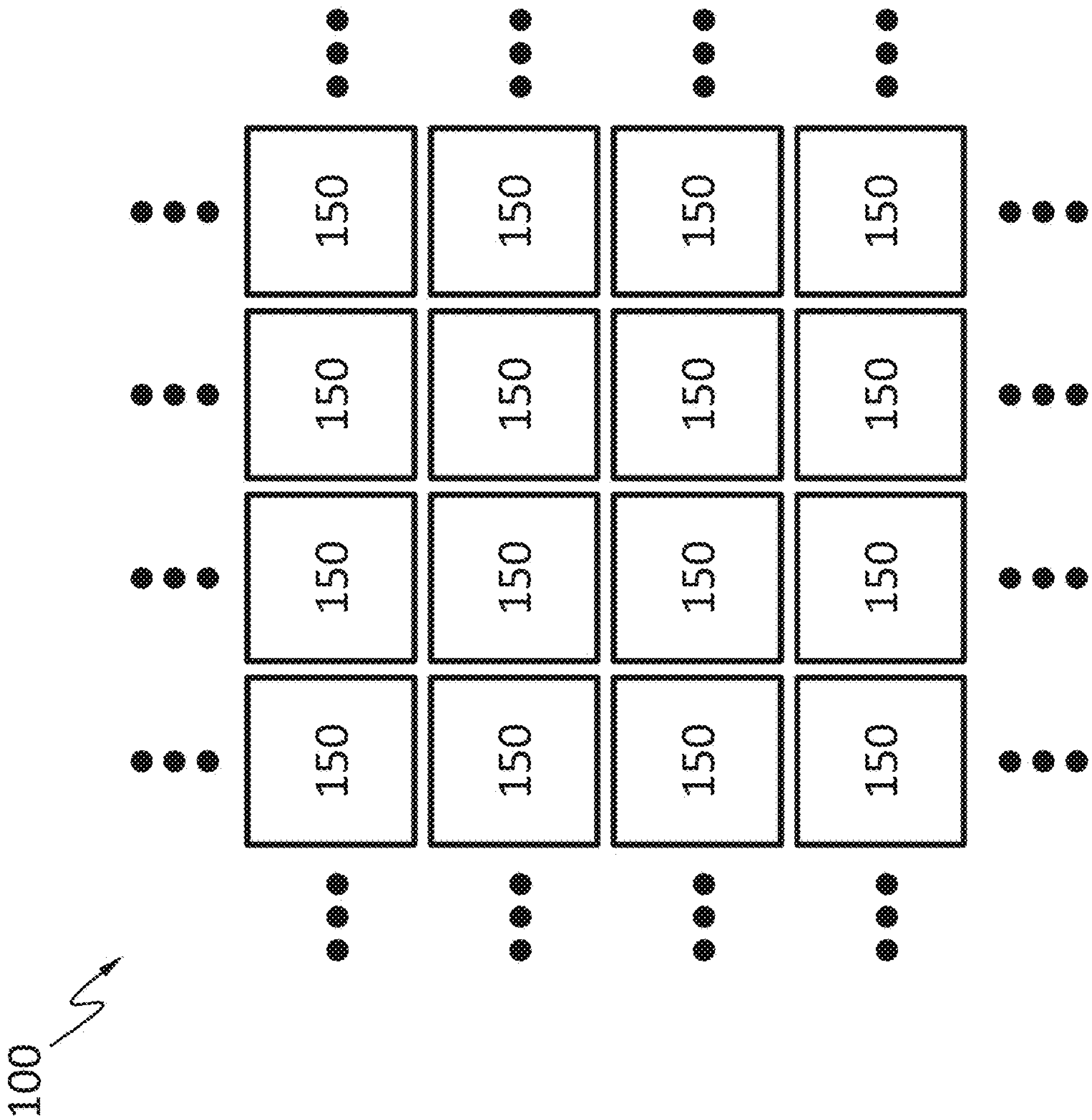



Fig. 2

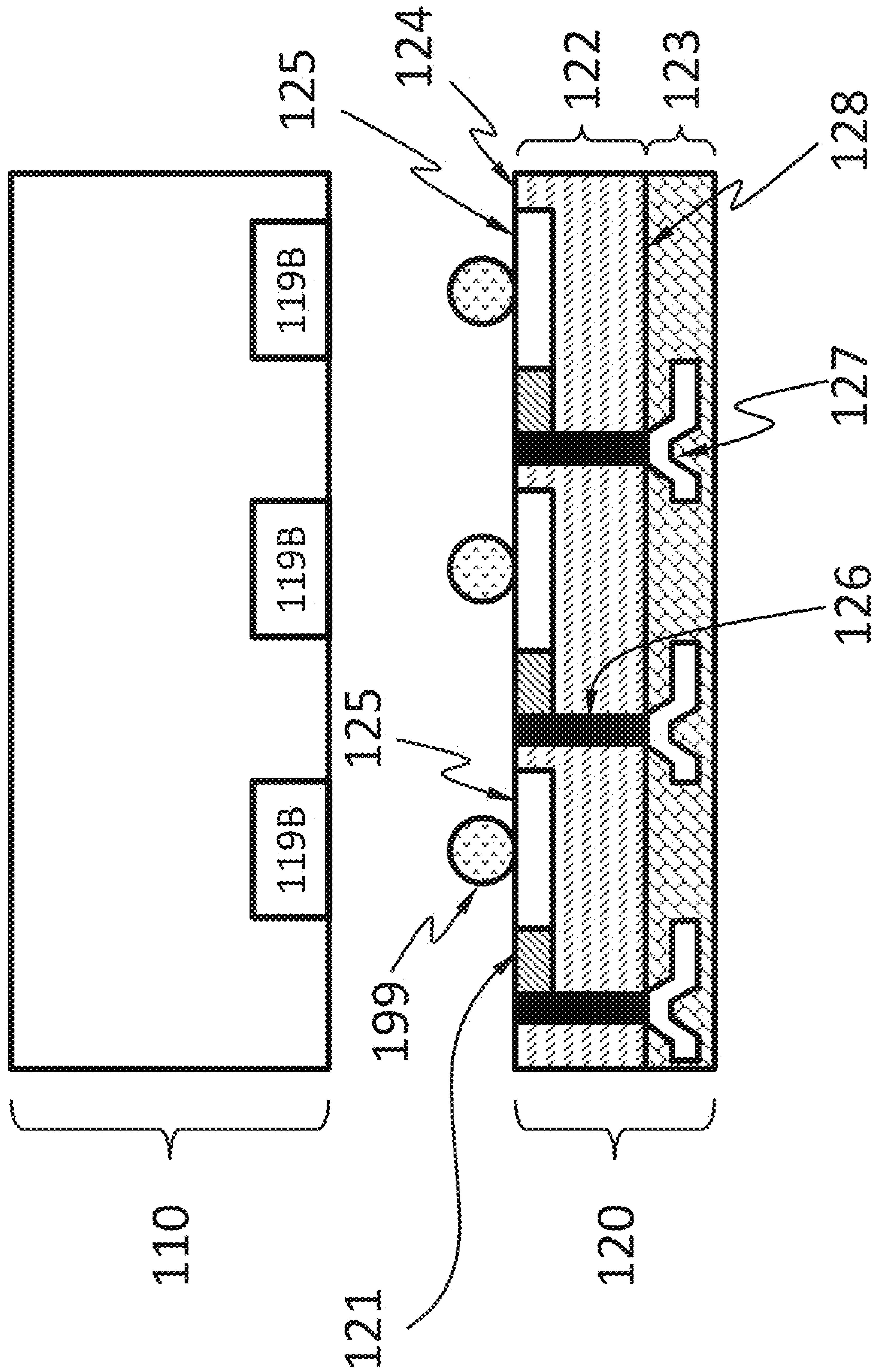
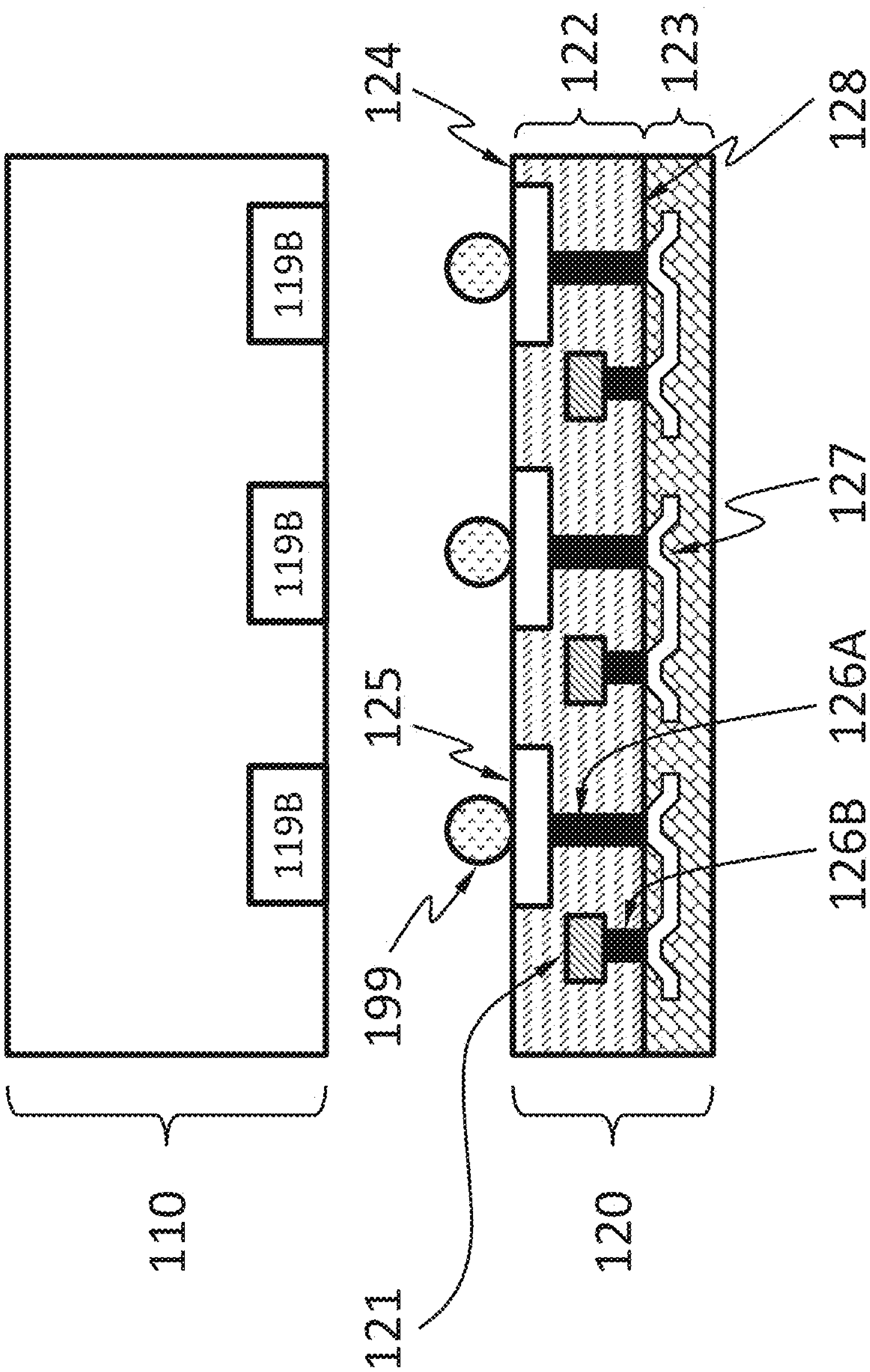



Fig. 3A



124
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119B
119B
119B
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126A
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126B
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121


Fig. 3B

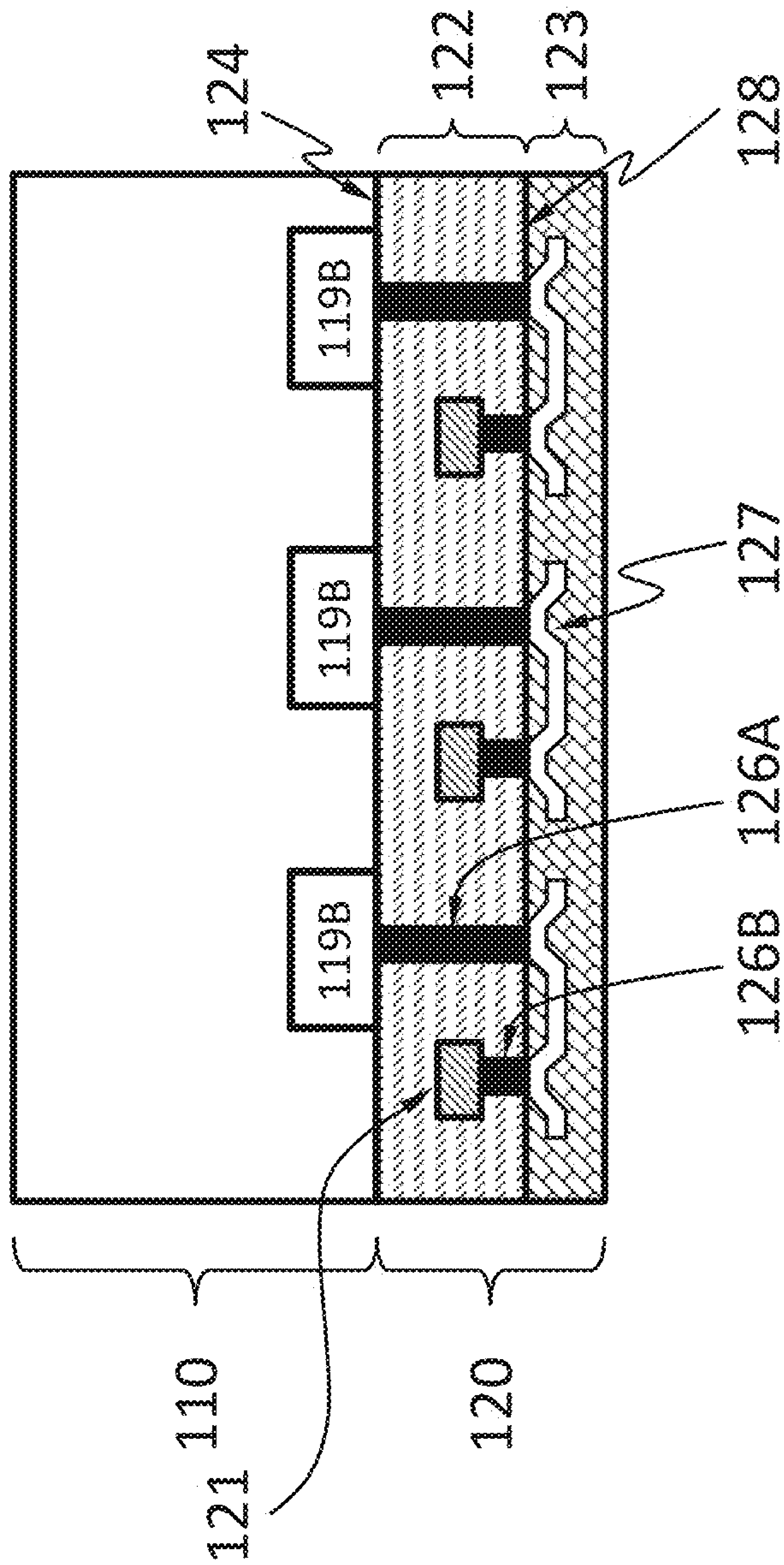


Fig. 3C

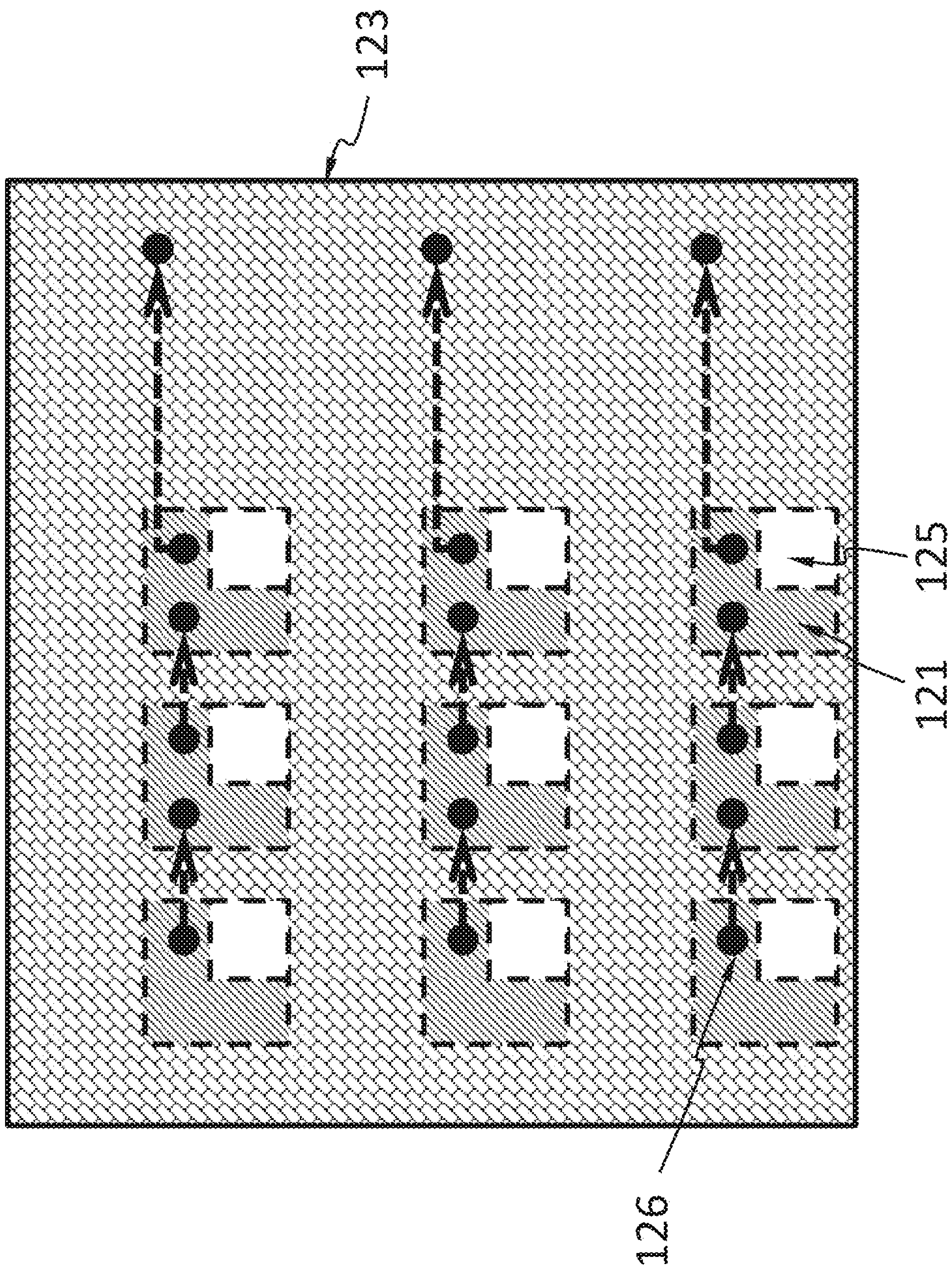


Fig. 4A

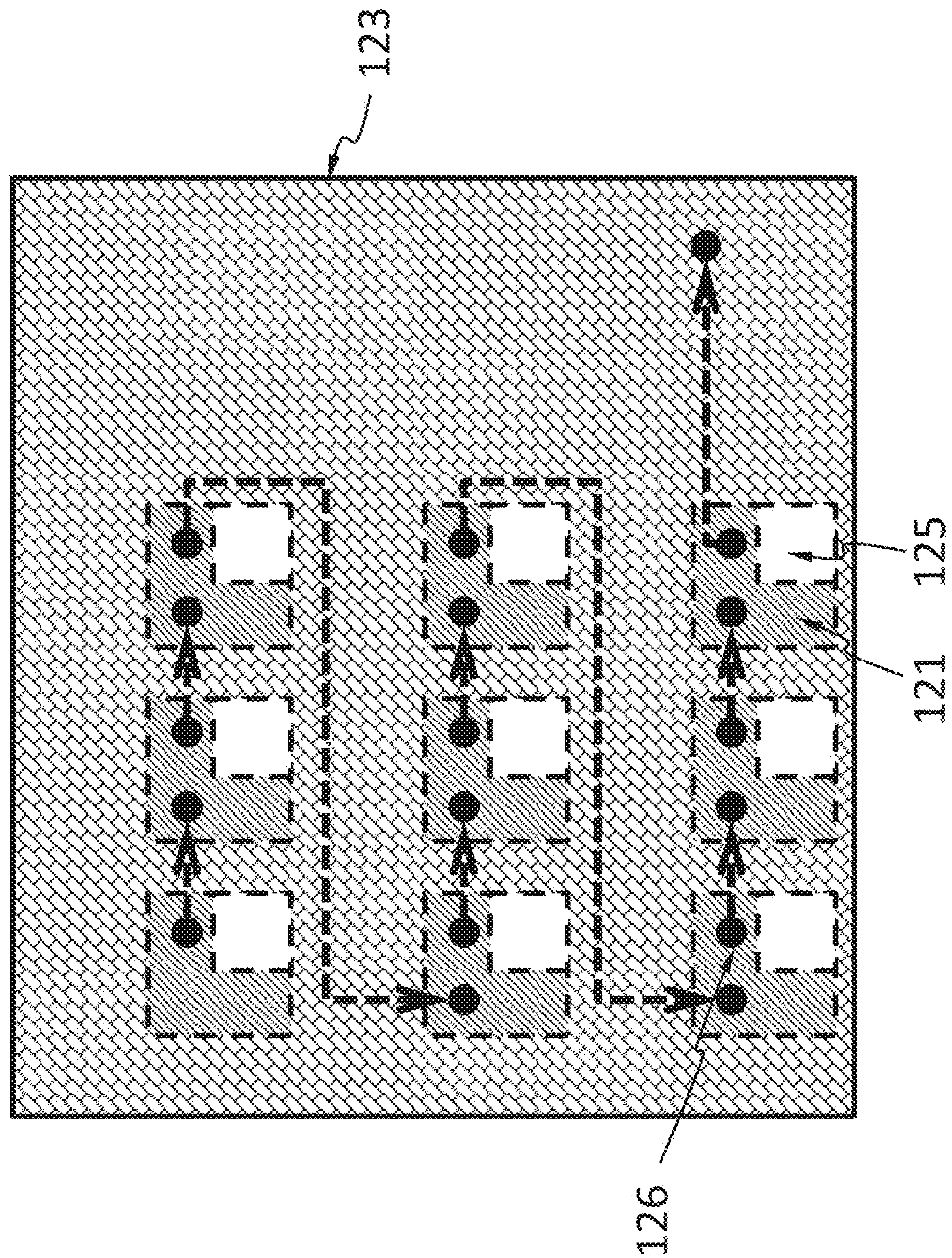


Fig. 4B

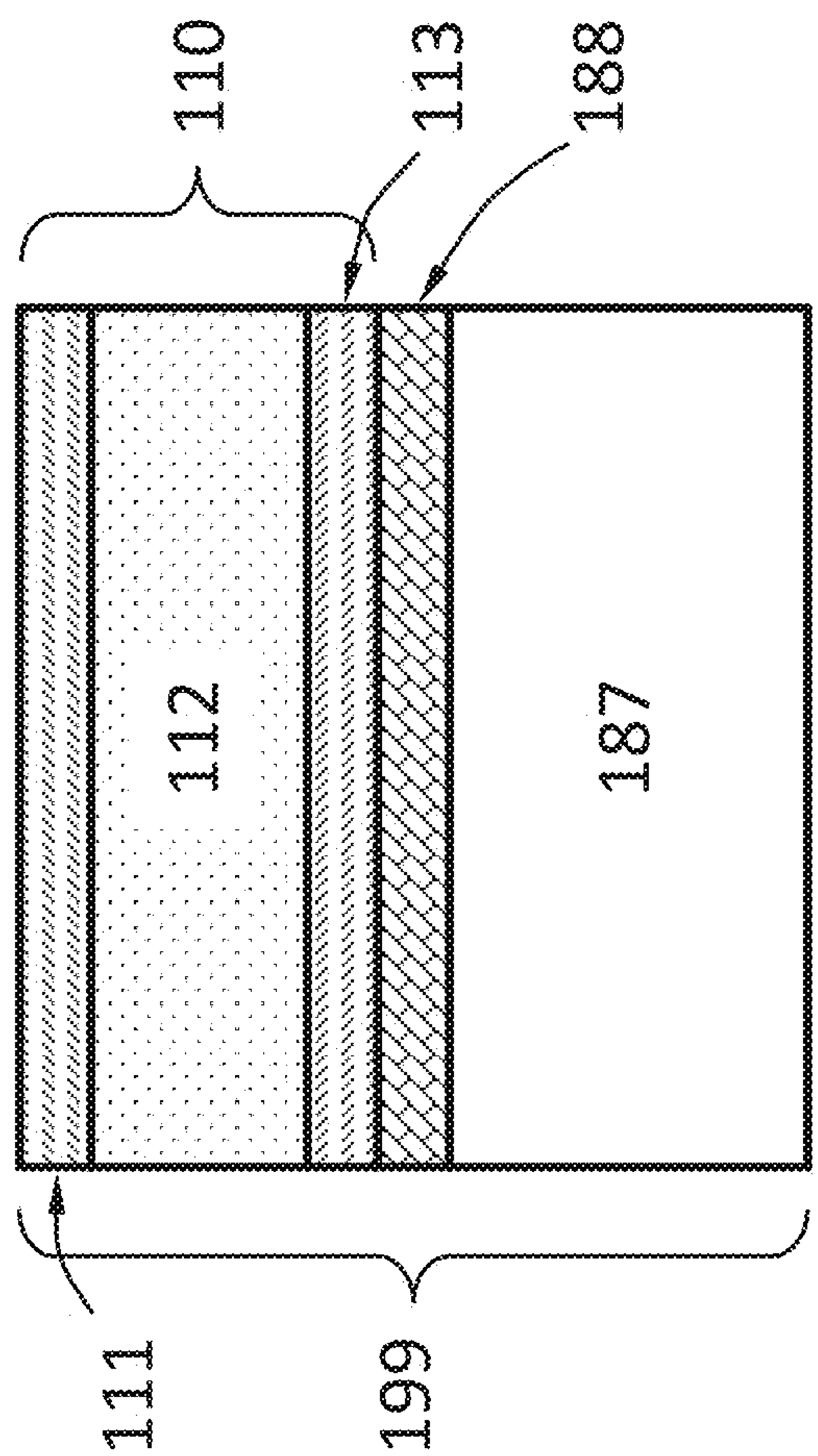


Fig. 5A

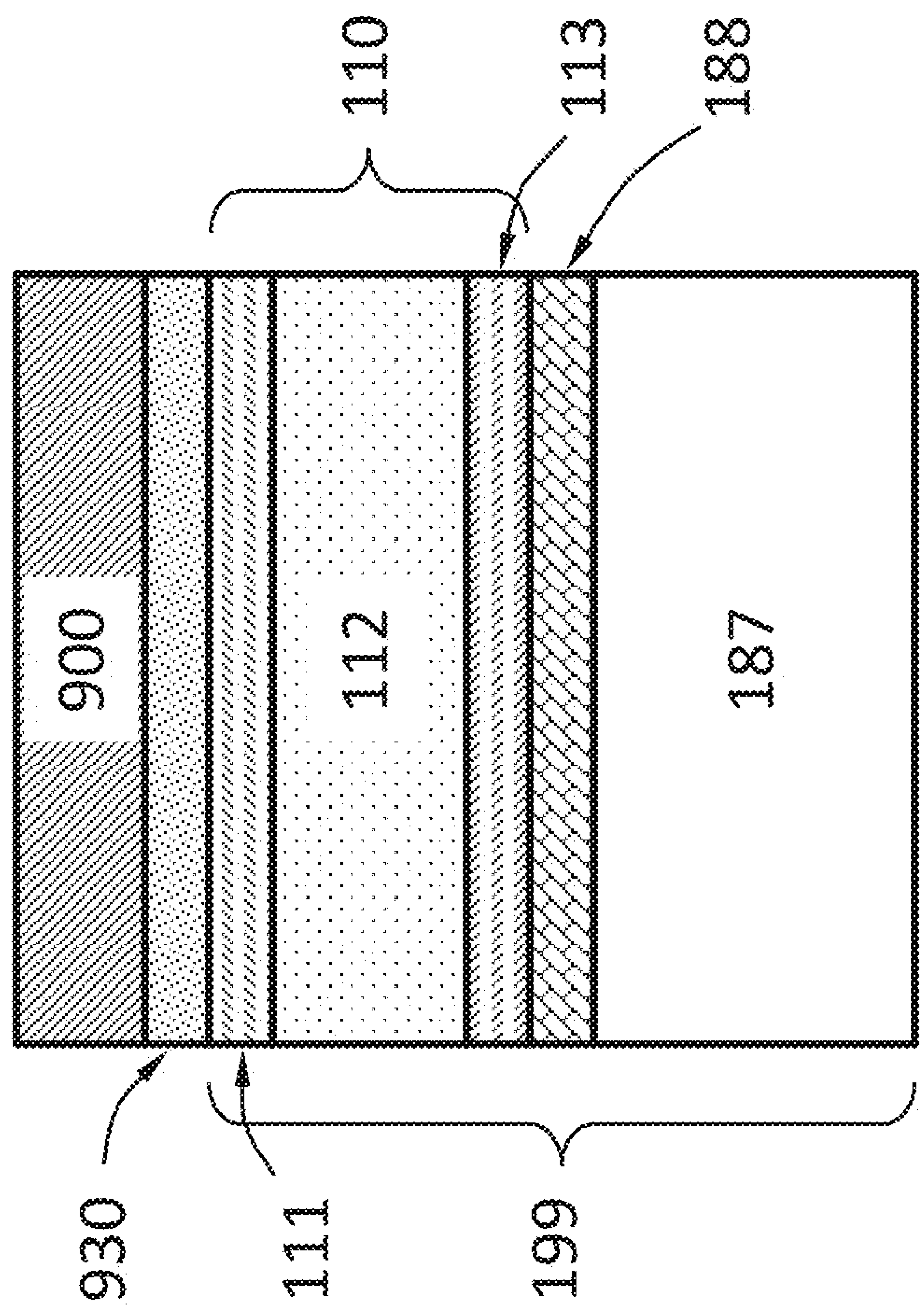


Fig. 5B

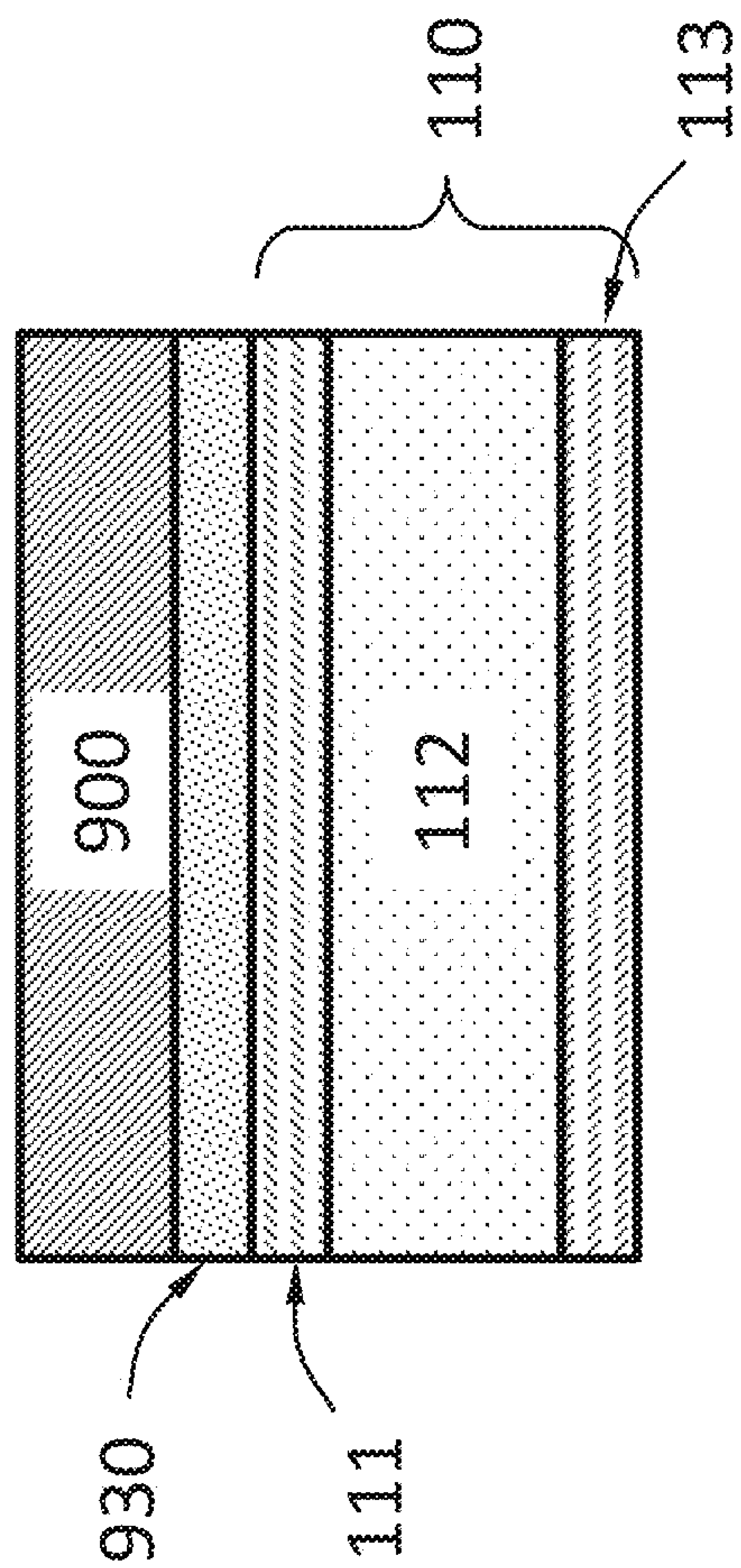


Fig. 5C

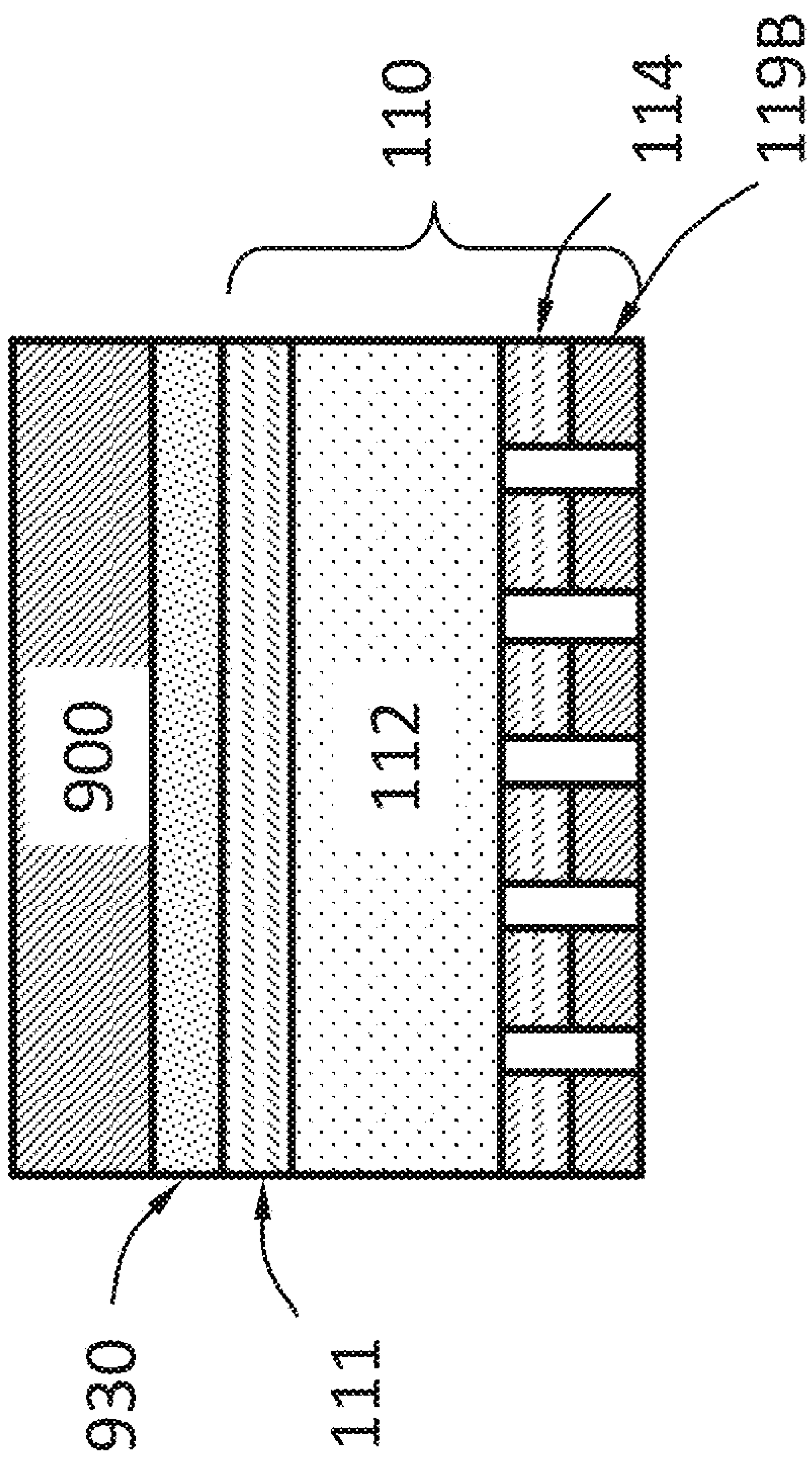


Fig. 5D

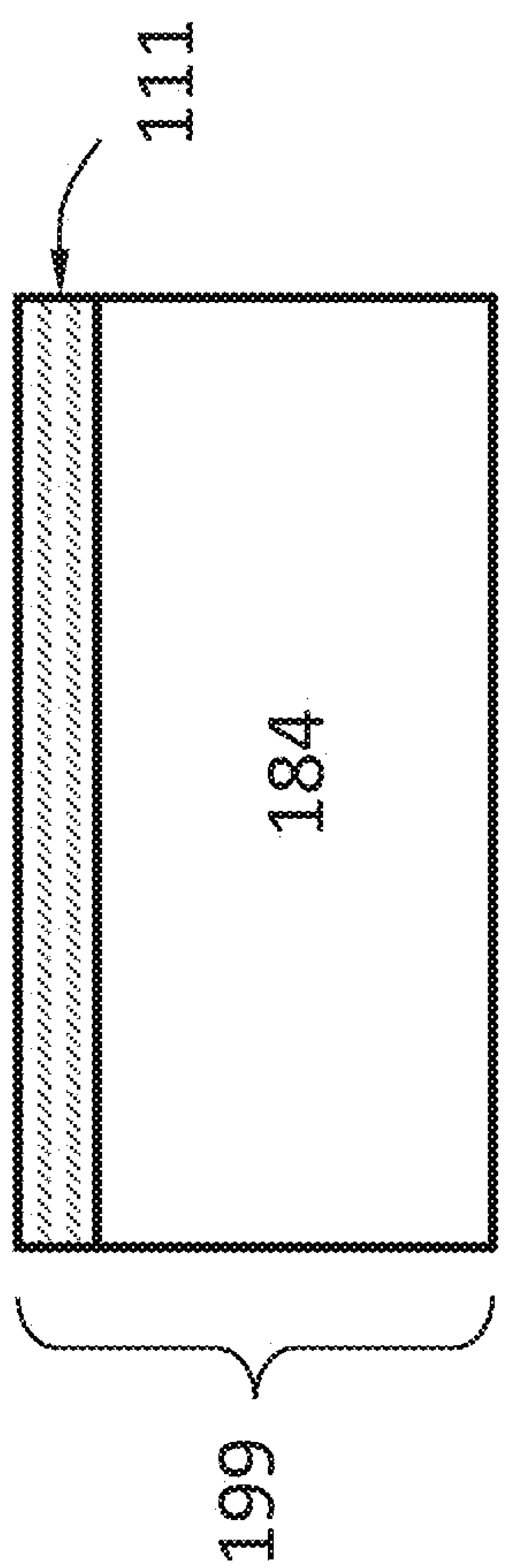


Fig. 6A

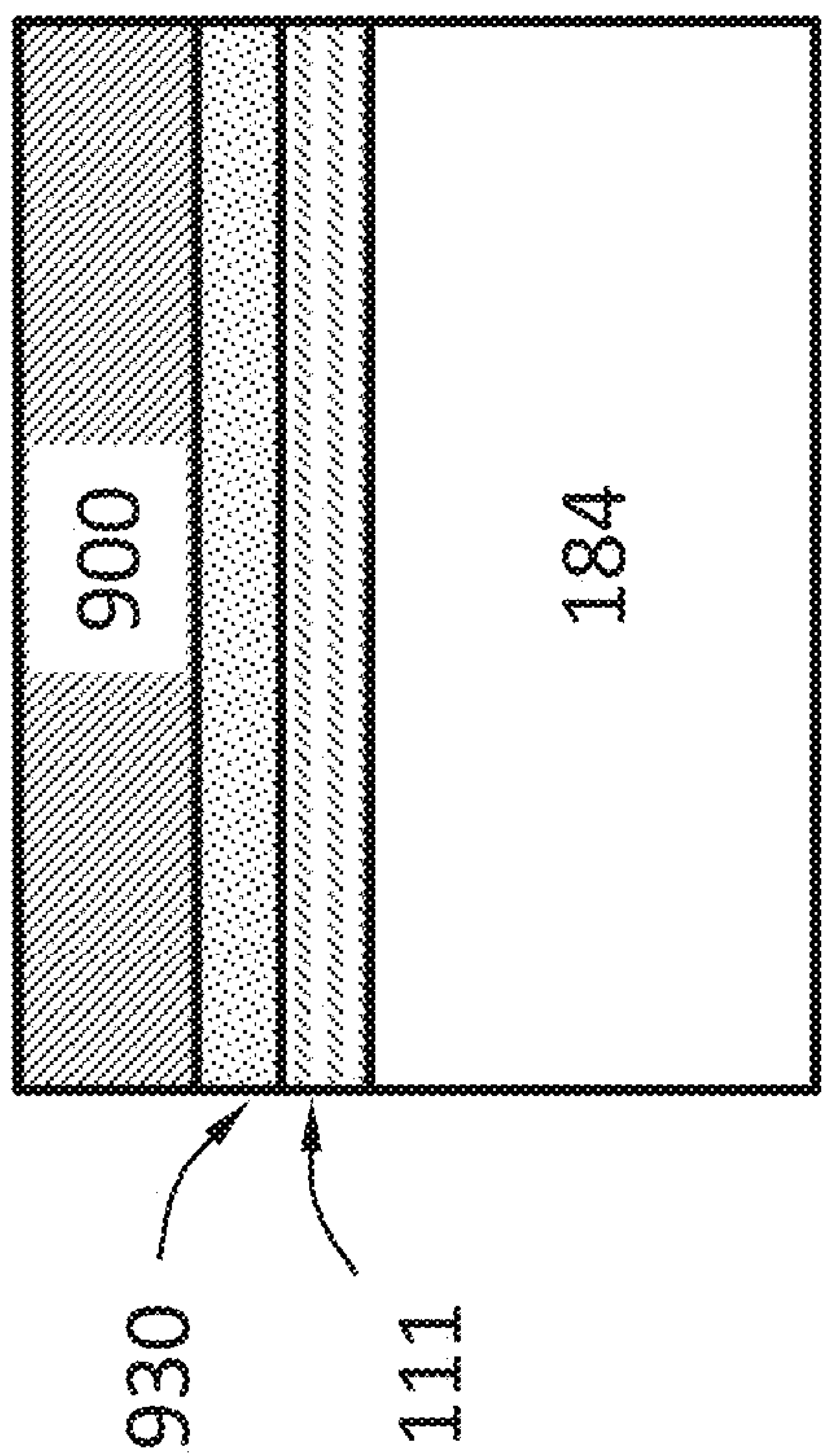


Fig. 6B

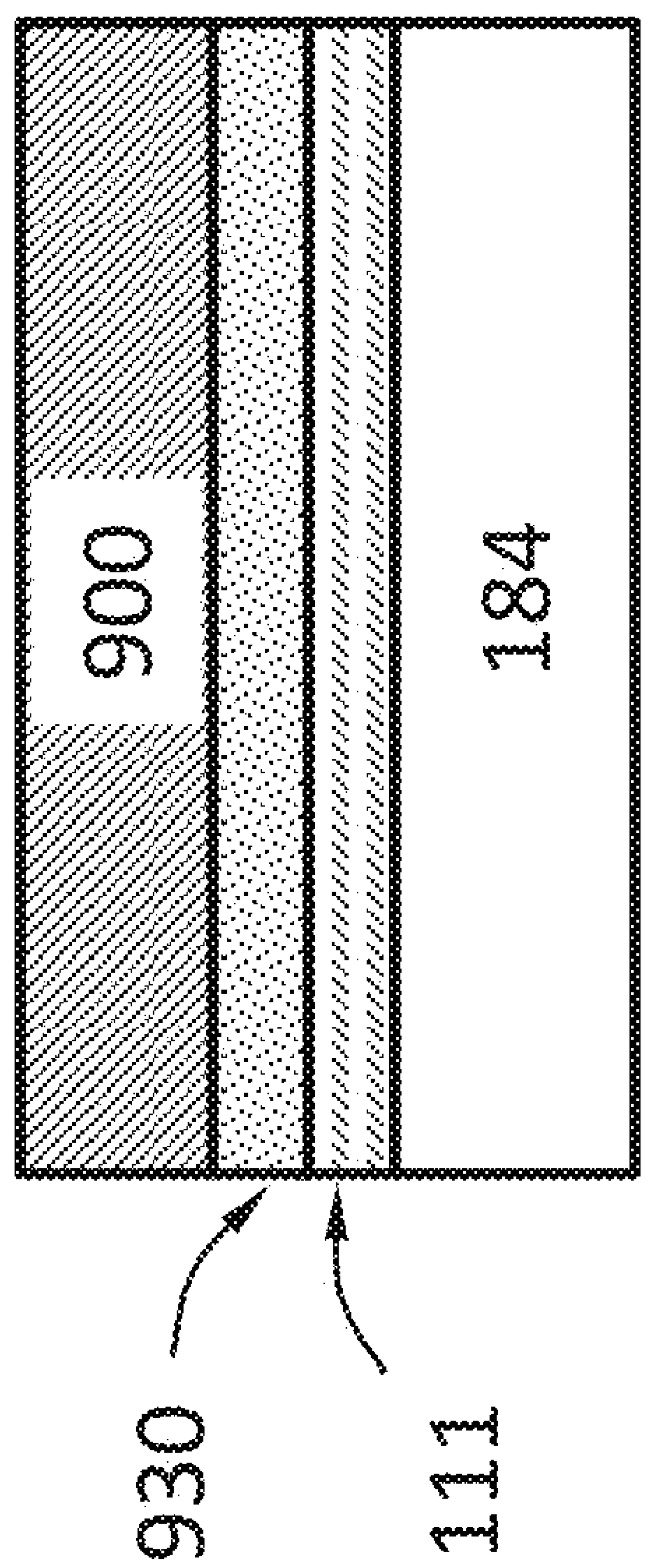


Fig. 6C

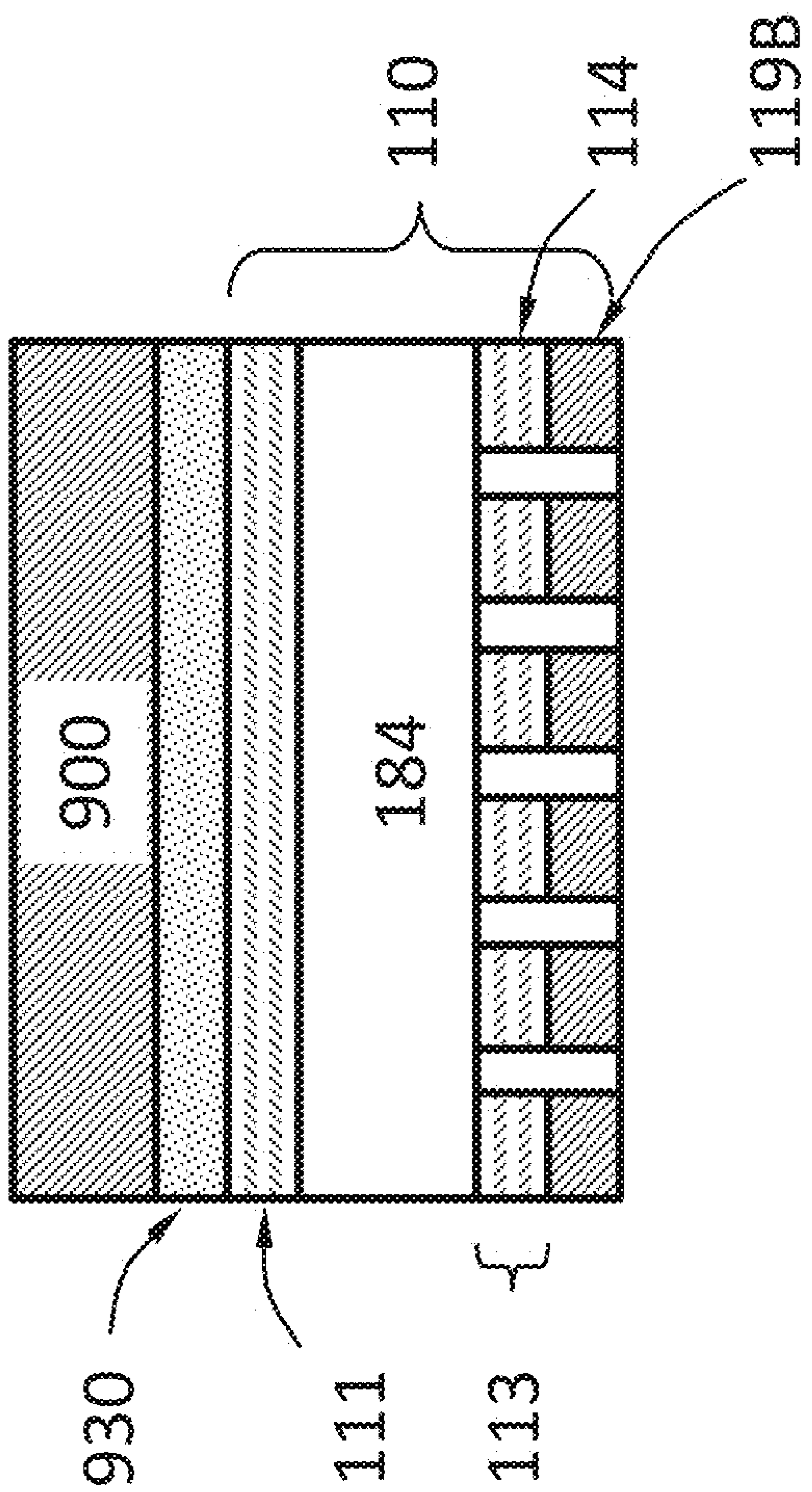


Fig. 6D

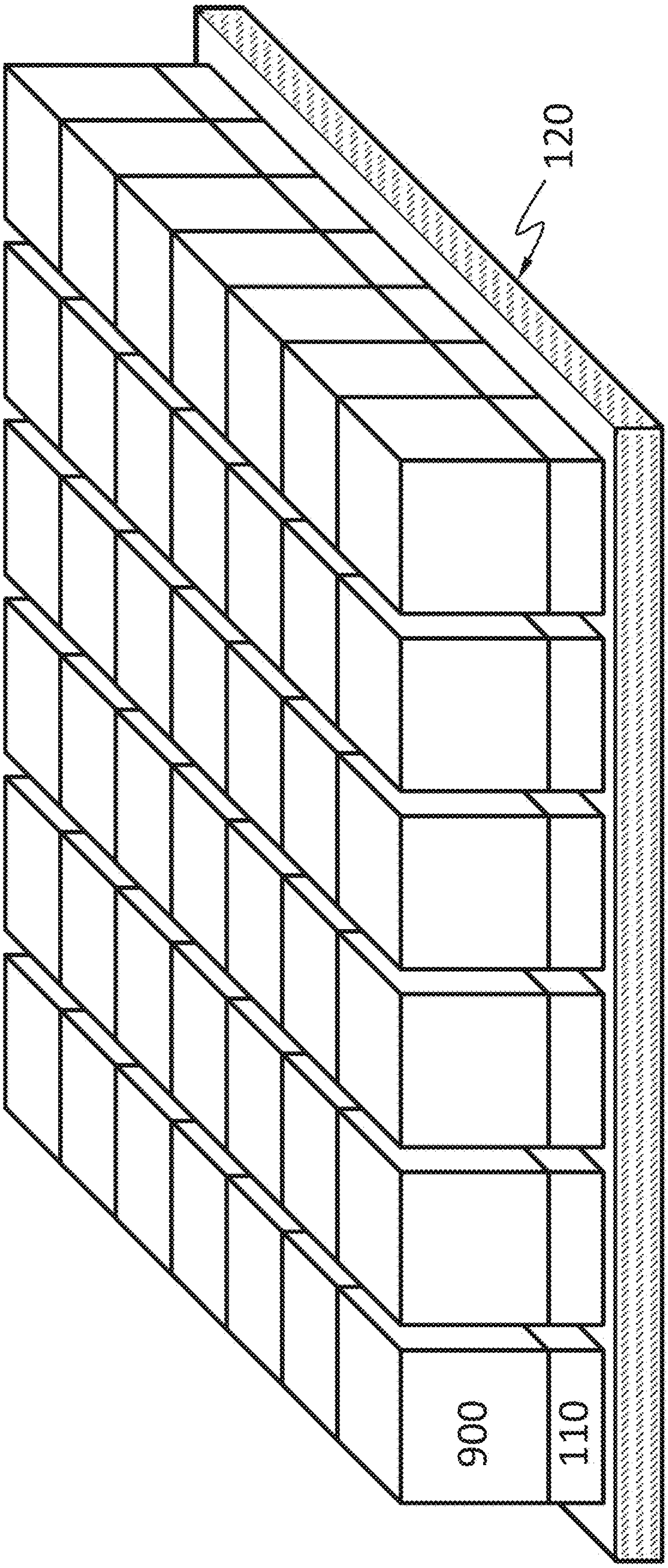


Fig. 7A

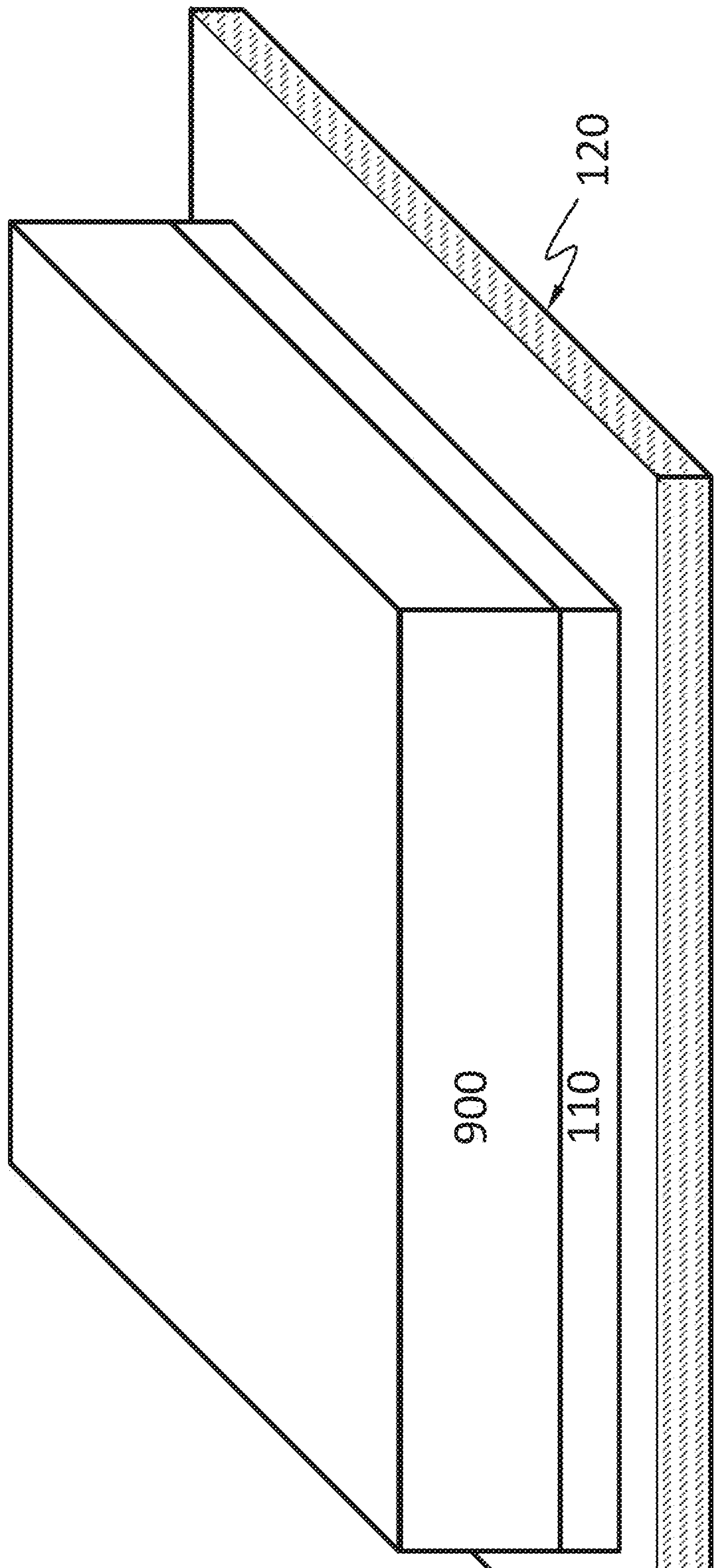


Fig. 7B

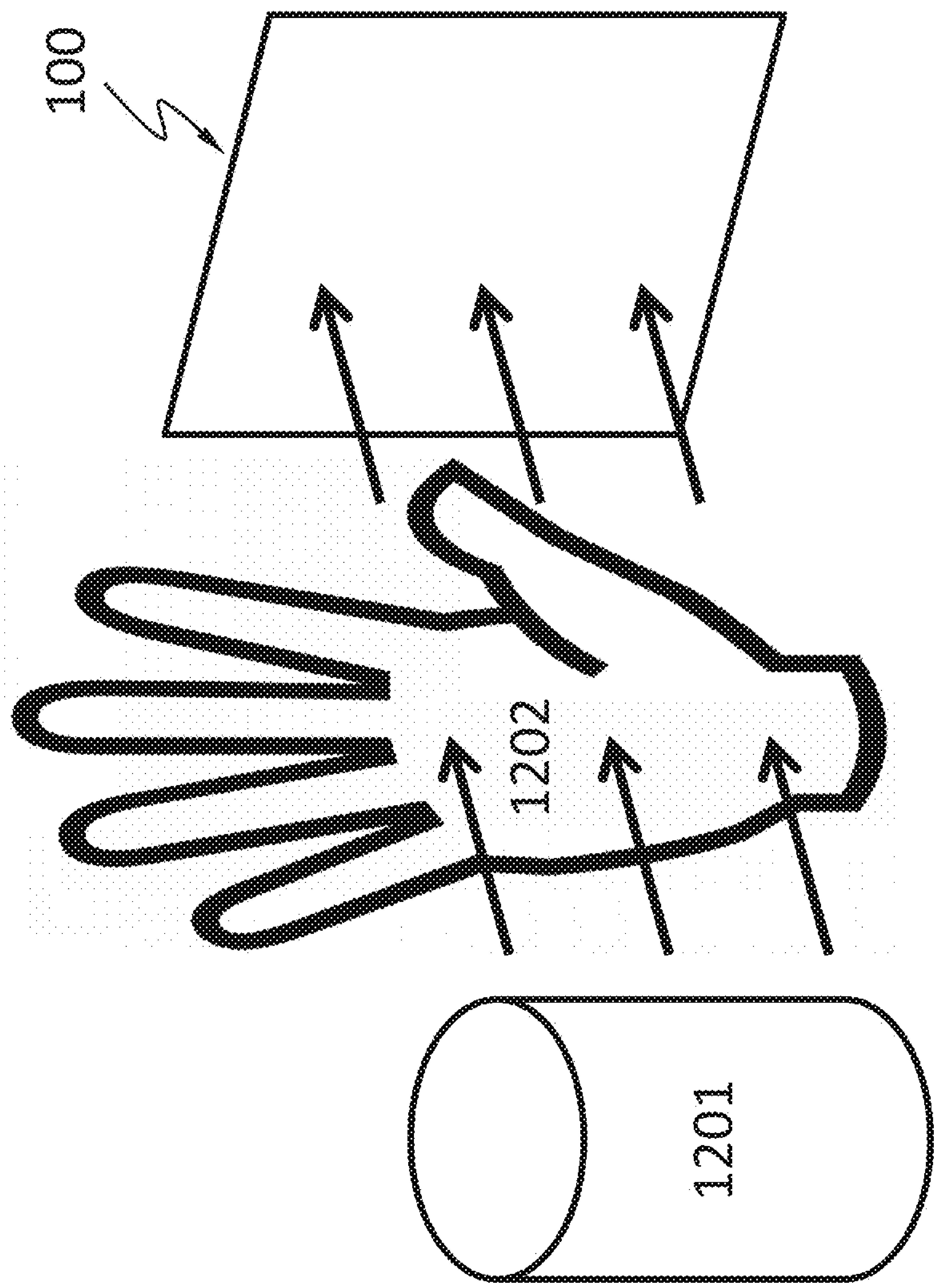


Fig. 8

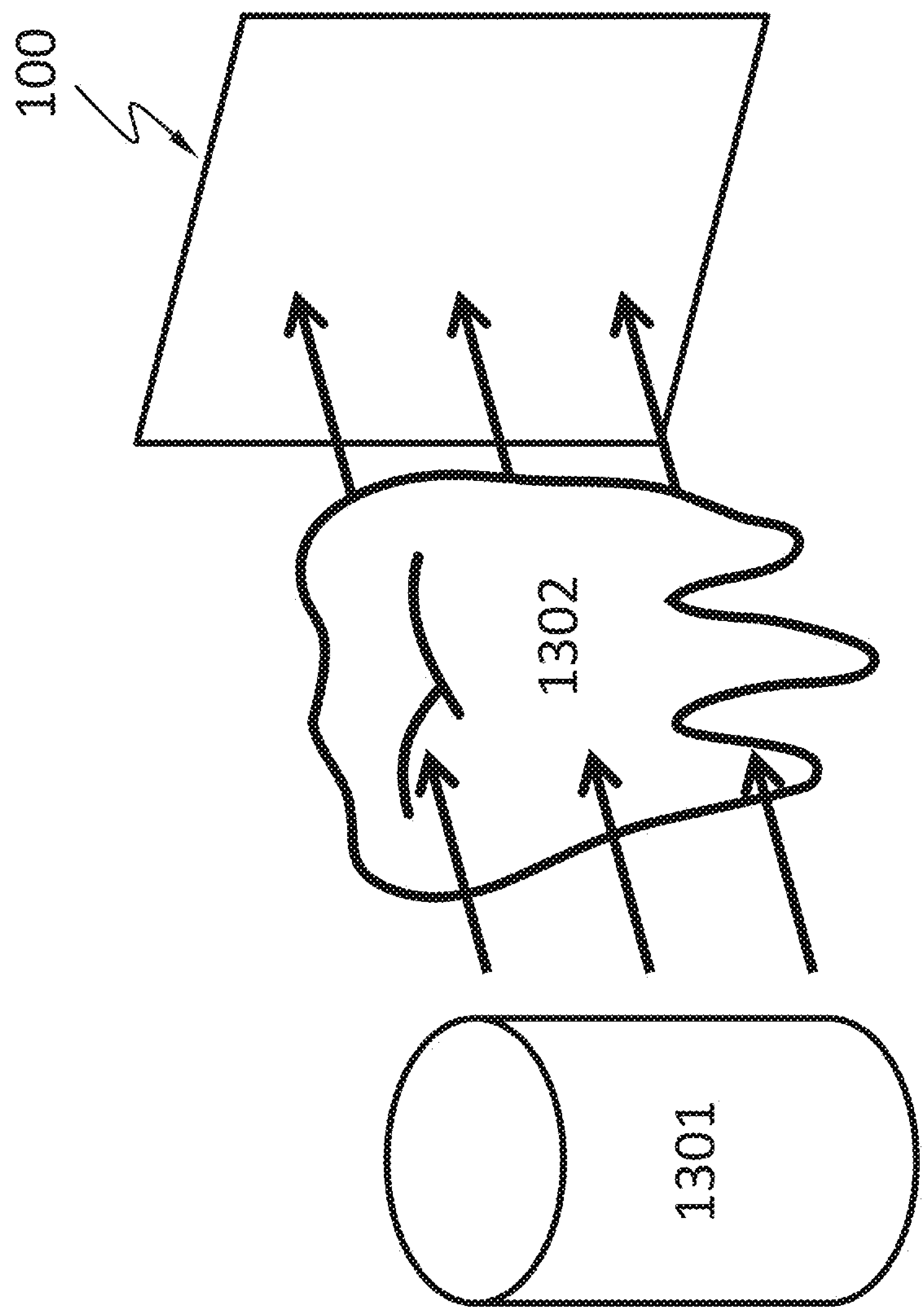


Fig. 9

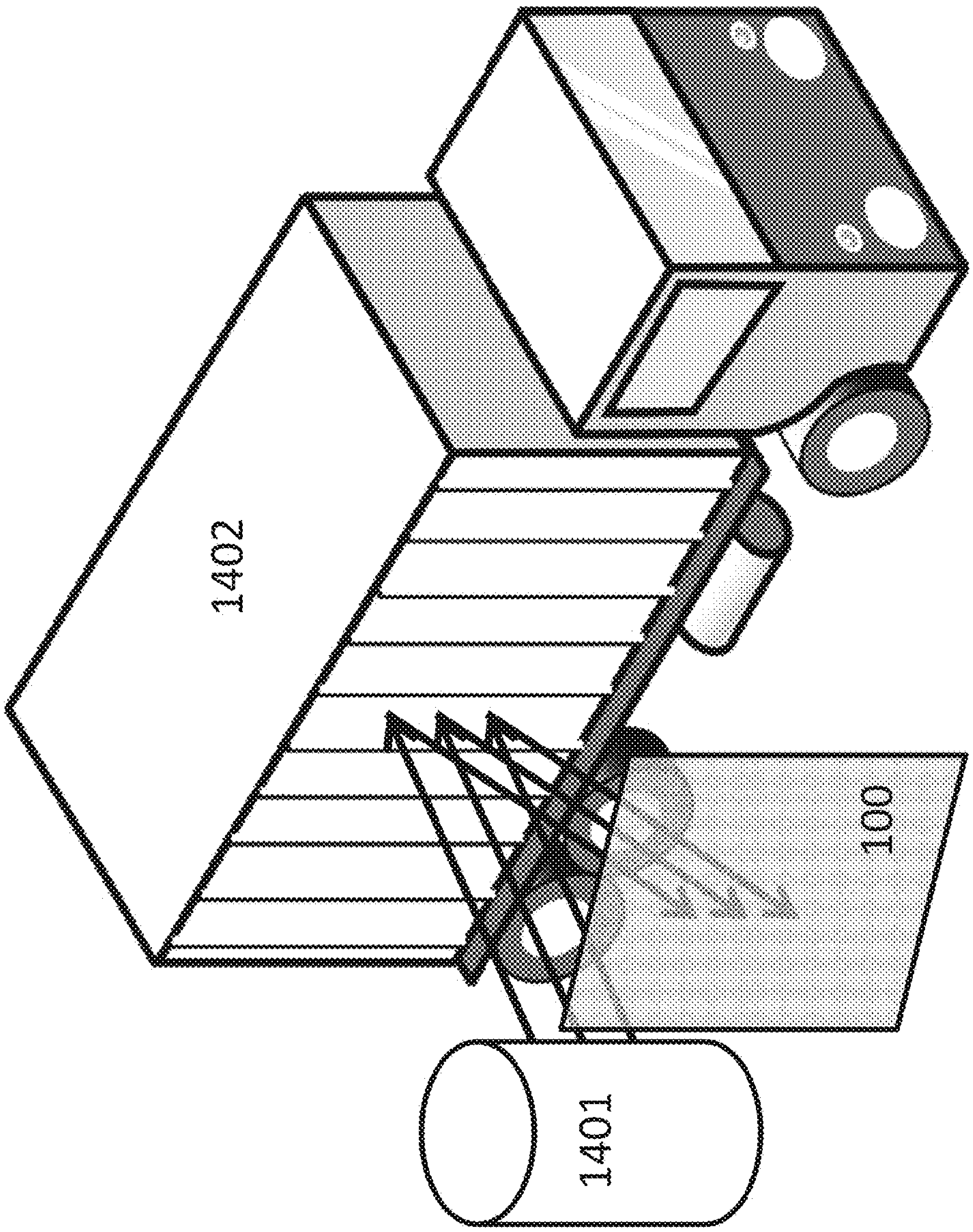


Fig. 10

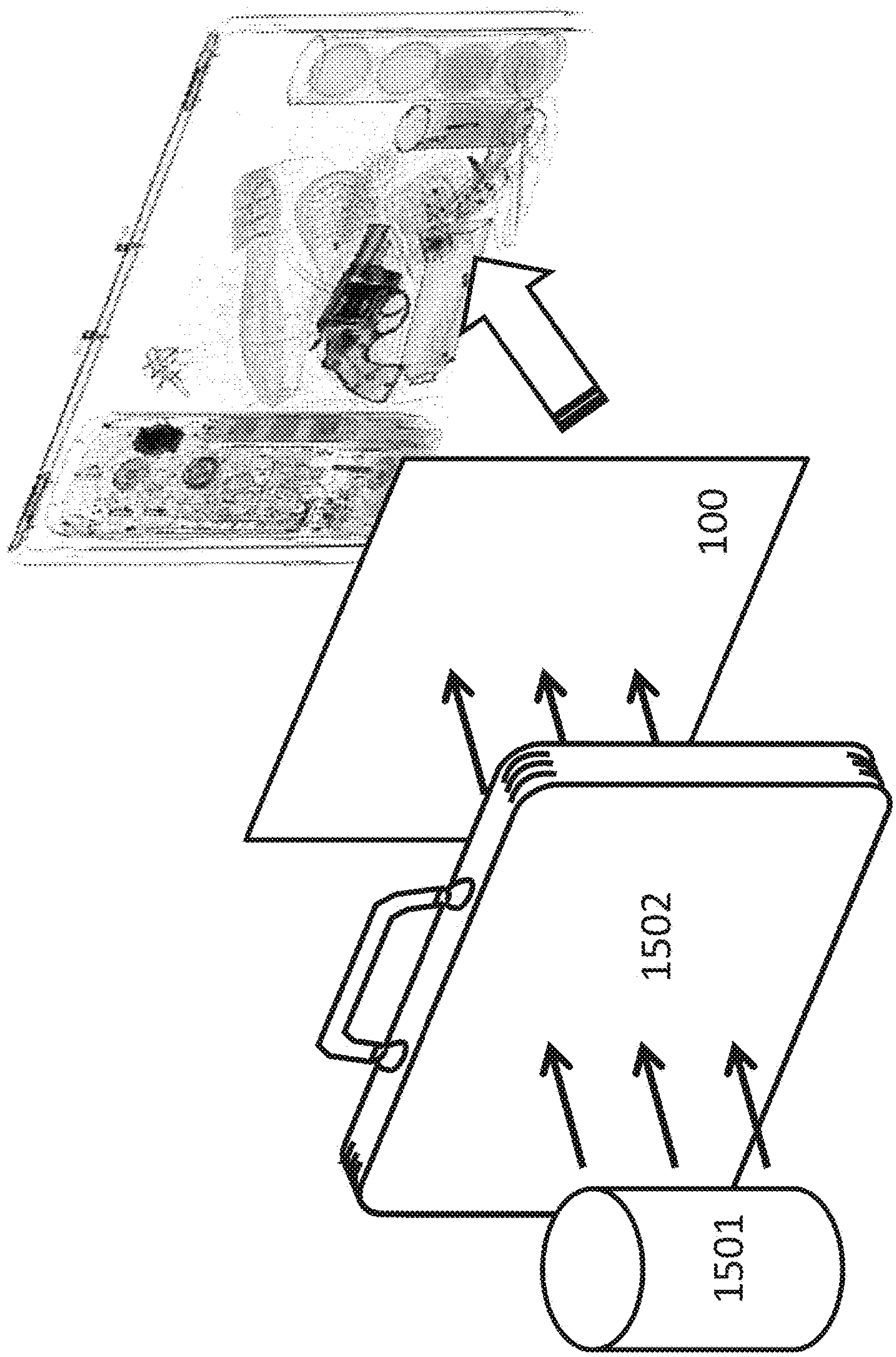


Fig. 11

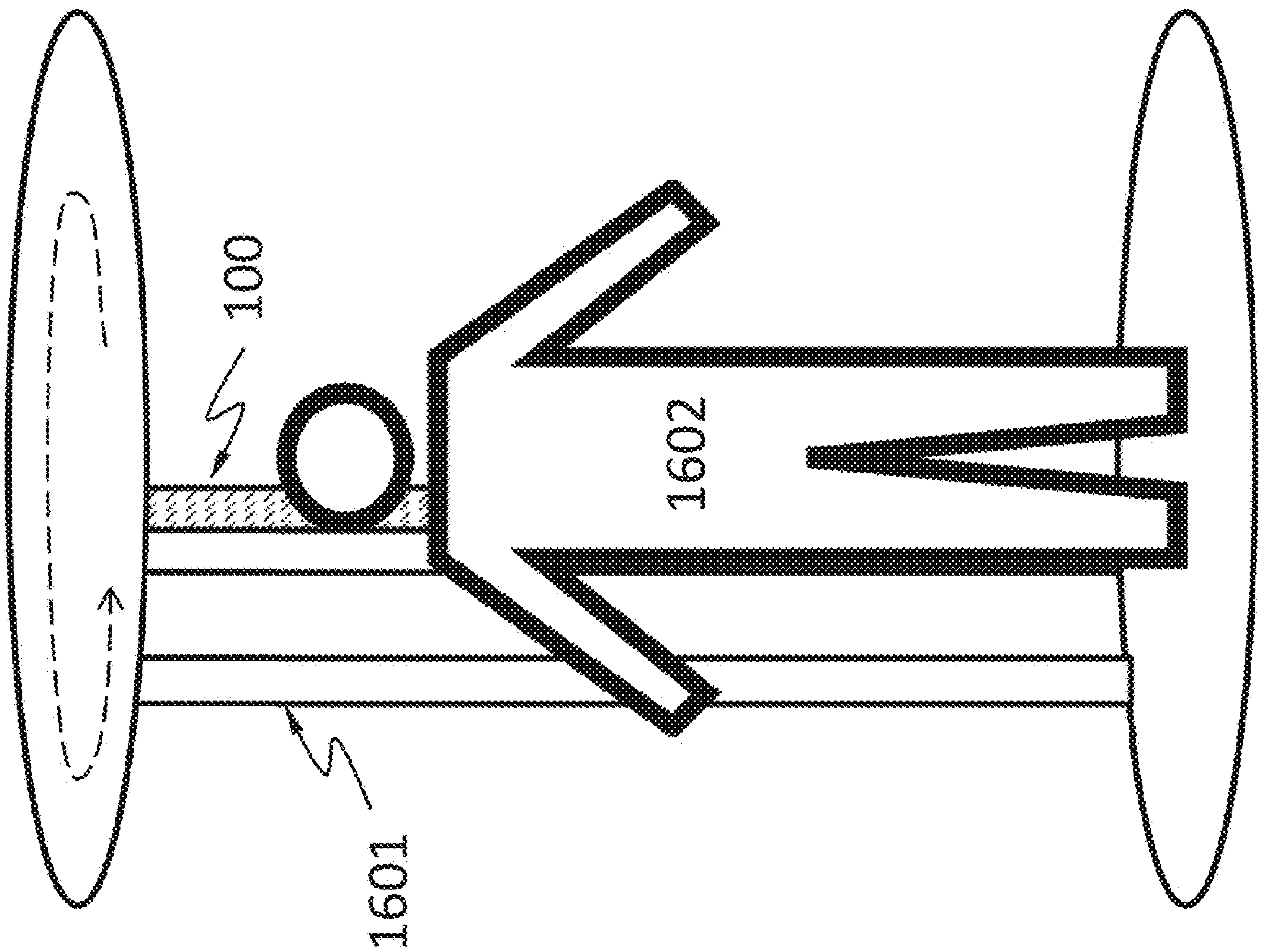


Fig. 12

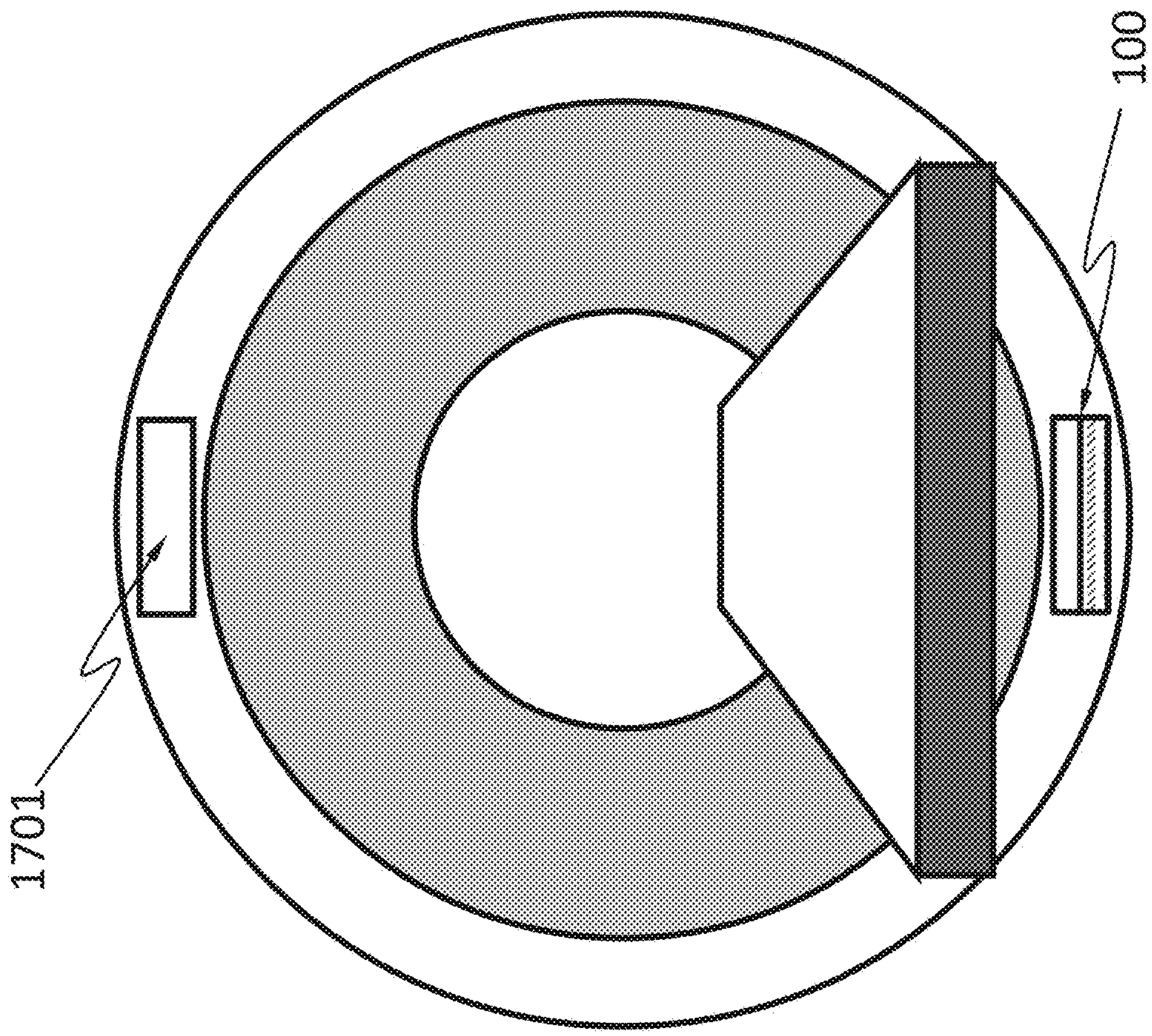


Fig. 13

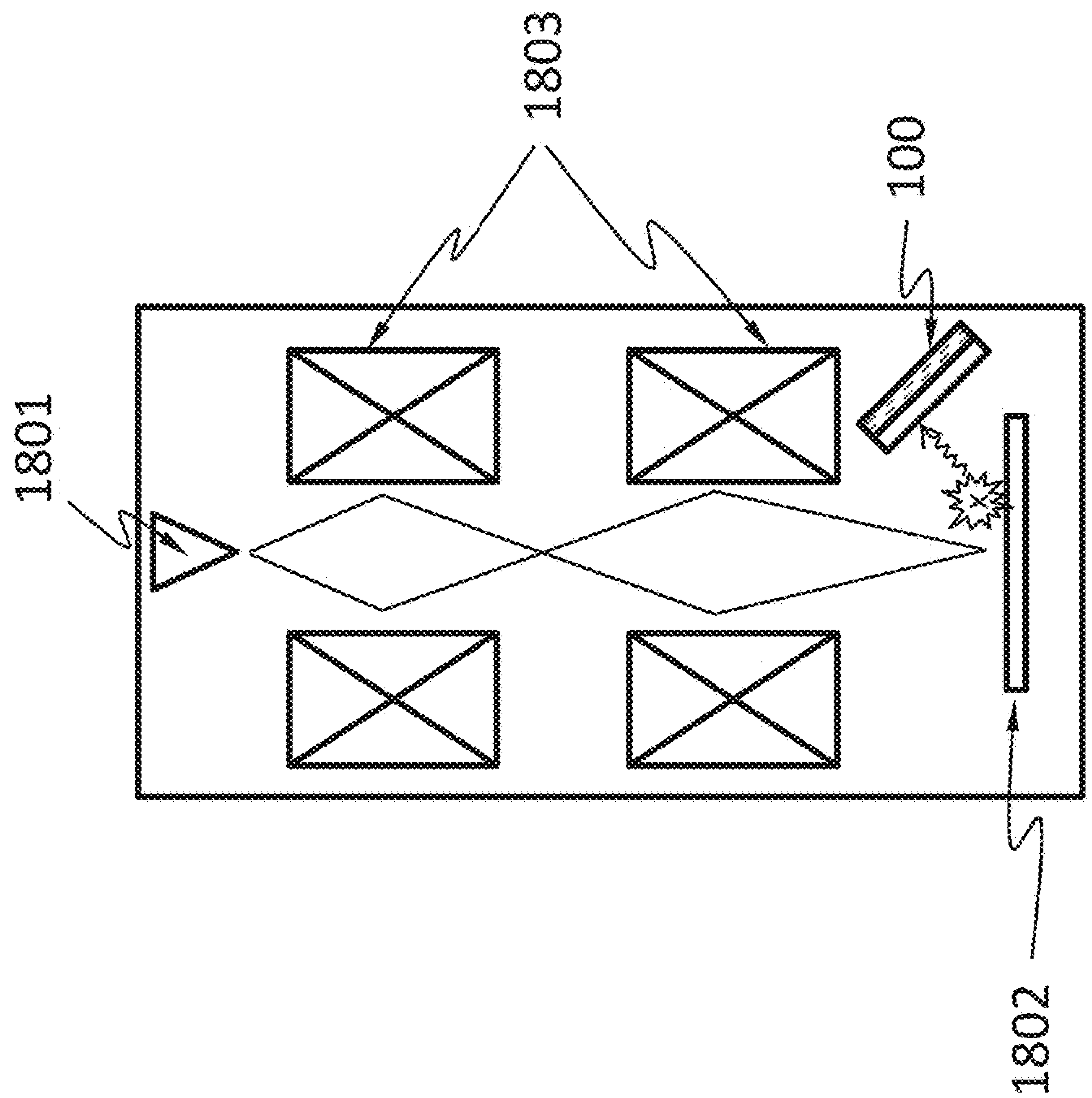


Fig. 14

# METHODS OF MAKING SEMICONDUCTOR X-RAY DETECTOR

## TECHNICAL FIELD

The disclosure herein relates to X-ray detectors, particularly relates to methods of making semiconductor X-ray detectors.

## BACKGROUND

X-ray detectors may be devices used to measure the flux, spatial distribution, spectrum or other properties of X-rays.

X-ray detectors may be used for many applications. One important application is imaging. X-ray imaging is a radiography technique and can be used to reveal the internal structure of a non-uniformly composed and opaque object such as the human body.

Early X-ray detectors for imaging include photographic plates and photographic films. A photographic plate may be a glass plate with a coating of light-sensitive emulsion. Although photographic plates were replaced by photographic films, they may still be used in special situations due to the superior quality they offer and their extreme stability. A photographic film may be a plastic film (e.g., a strip or sheet) with a coating of light-sensitive emulsion.

In the 1980s, photostimulable phosphor plates (PSP plates) became available. A PSP plate may contain a phosphor material with color centers in its lattice. When the PSP plate is exposed to X-ray, electrons excited by X-ray are trapped in the color centers until they are stimulated by a laser beam scanning over the plate surface. As the plate is scanned by laser, trapped excited electrons give off light, which is collected by a photo multiplier tube. The collected light is converted into a digital image. In contrast to photographic plates and photographic films, PSP plates can be reused.

Another kind of X-ray detectors are X-ray image intensifiers. Components of an X-ray image intensifier are usually sealed in a vacuum. In contrast to photographic plates, photographic films, and PSP plates, X-ray image intensifiers may produce real-time images, i.e., do not require post-exposure processing to produce images. X-ray first hits an input phosphor (e.g., cesium iodide) and is converted to visible light. The visible light then hits a photocathode (e.g., a thin metal layer containing cesium and antimony compounds) and causes emission of electrons. The number of emitted electrons is proportional to the intensity of the incident X-ray. The emitted electrons are projected, through electron optics, onto an output phosphor and cause the output phosphor to produce a visible-light image.

Scintillators operate somewhat similarly to X-ray image intensifiers in that scintillators (e.g., sodium iodide) absorb X-ray and emit visible light, which can then be detected by a suitable image sensor for visible light. In scintillators, the visible light spreads and scatters in all directions and thus reduces spatial resolution. Reducing the scintillator thickness helps to improve the spatial resolution but also reduces absorption of X-ray. A scintillator thus has to strike a compromise between absorption efficiency and resolution.

Semiconductor X-ray detectors largely overcome this problem by direct conversion of X-ray into electric signals. A semiconductor X-ray detector may include a semiconductor layer that absorbs X-ray in wavelengths of interest. When an X-ray photon is absorbed in the semiconductor layer, multiple charge carriers (e.g., electrons and holes) are generated and swept under an electric field towards electrical contacts on the semiconductor layer. Cumbersome heat management required in currently available semiconductor X-ray detectors (e.g., Medipix) can make a detector with a large area and a large number of pixels difficult or impossible to produce.

## SUMMARY

Disclosed herein is a method of making an apparatus suitable for detecting x-ray, the method comprising: attaching a chip comprising an X-ray absorption layer to a surface of a substrate, wherein the surface is electrically conductive; thinning the chip; forming an electrical contact in the chip; bonding an electronic layer to the chip such that the electrical contact of the chip is electrically connected to an electrical contact of the electronic layer.

According to an embodiment, the substrate is not removed from the chip.

According to an embodiment, the substrate has a mass attenuation coefficient less than 1000 $m^2/kg$ for X-ray.

According to an embodiment, the substrate comprises silicon, glass, silicon oxide, Al, Cr, Ti, or a combination thereof.

According to an embodiment, thinning comprises reducing a thickness of the chip to 200 microns or less, 100 microns or less, or 50 microns or less.

According to an embodiment, the chip comprises GaAs.

According to an embodiment, the GaAs is not doped with chromium.

According to an embodiment, attaching the chip to the surface of the substrate comprises depositing a layer of metal to the chip.

According to an embodiment, the method further comprises forming a diode in the chip.

According to an embodiment, the method further comprises forming discrete electrical contacts on the chip.

Disclosed herein is a method of making an apparatus suitable for detecting x-ray, the method comprising: attaching a chip comprising an X-ray absorption layer to a surface of a substrate, wherein the surface is electrically conductive, wherein the chip comprises a sacrificial substrate, a second doped region on the sacrificial substrate; exposing the second doped region by removing the sacrificial substrate; forming an electrical contact on the second doped region; bonding an electronic layer to the chip such that the electrical contact of the chip is electrically connected to an electrical contact of the electronic layer.

According to an embodiment, the method further comprises an etch stop layer between the sacrificial substrate and the second doped region.

According to an embodiment, the method further comprises an intrinsic region, wherein the intrinsic region and the sacrificial substrate sandwich the second doped region.

According to an embodiment, the intrinsic region has a thickness of less than 75 microns, less than 100 microns, less than 125 microns, or less than 200 microns.

According to an embodiment, the method further comprises a lightly doped region, wherein the lightly doped region and the sacrificial substrate sandwich the second doped region.

According to an embodiment, the lightly doped region has a thickness of less than 75 microns, less than 100 microns, less than 125 microns, or less than 200 microns.

According to an embodiment, the second doped region is an epitaxial layer.

According to an embodiment, the method further comprises a first doped region, wherein the second doped region is sandwiched between the first doped region and the sacrificial substrate.

According to an embodiment, the first doped region is heavily doped.

According to an embodiment, the first doped region is an epitaxial layer.

According to an embodiment, the first and second doped regions form a diode.

According to an embodiment, the electric contact of the chip comprises structures extending into the X-ray absorption layer.

## BRIEF DESCRIPTION OF FIGURES

FIG. **1**A schematically shows a cross-sectional view of the detector, according to an embodiment.

FIG. **1**B schematically shows a detailed cross-sectional view of the detector, according to an embodiment.

FIG. **1**C schematically shows an alternative detailed cross-sectional view of the detector, according to an embodiment.

FIG. **1**D schematically shows that the electrical contacts on the X-ray absorption layer may have structures extending into the X-ray absorption layer.

FIG. **2** schematically shows that the device may have an array of pixels, according to an embodiment.

FIG. **3**A schematically shows the electronics layer, according to an embodiment.

FIG. **3**B schematically shows the electronics layer, according to an embodiment.

FIG. **3**C schematically shows the electronics layer, according to an embodiment.

FIG. **4**A shows a top view of the RDL in FIG. **3**A, according to an embodiment.

FIG. **4**B shows a top view of the RDL in FIG. **3**A, according to an embodiment.

FIGS. **5**A-**5**D schematically show a flow of making the X-ray absorption layer, according to an embodiment.

FIGS. **6**A-**6**D schematically show a flow of making the X-ray absorption layer, according to an embodiment.

FIG. **7**A shows that multiple chips may be bonded to a single electronic layer, where each chip may include an X-ray absorption layer, according to an embodiment.

FIG. **7**B shows that a single X-ray absorption layer may be bonded to a single electronic layer, according to an embodiment.

FIG. **8** schematically shows a system comprising the semiconductor X-ray detector described herein, suitable for medical imaging such as chest X-ray radiography, abdominal X-ray radiography, etc., according to an embodiment

FIG. **9** schematically shows a system comprising the semiconductor X-ray detector described herein suitable for dental X-ray radiography, according to an embodiment.

FIG. **10** schematically shows a cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **11** schematically shows another cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **12** schematically shows a full-body scanner system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **13** schematically shows an X-ray computed tomography (X-ray CT) system comprising the semiconductor X-ray detector described herein, according to an embodiment.

FIG. **14** schematically shows an electron microscope comprising the semiconductor X-ray detector described herein, according to an embodiment.

## DETAILED DESCRIPTION

FIG. **1**A schematically shows a cross-sectional view of the detector **100**, according to an embodiment. The detector **100** may include an X-ray absorption layer **110** and an electronics layer **120** (e.g., an ASIC) for processing or analyzing electrical signals incident X-ray generates in the X-ray absorption layer **110**. In an embodiment, the detector **100** does not comprise a scintillator. The X-ray absorption layer **110** may include a semiconductor material such as, silicon, germanium, GaAs, CdTe, CdZnTe, or a combination thereof. The semiconductor may have a high mass attenuation coefficient for the X-ray energy of interest.

As shown in a detailed cross-sectional view of the detector **100** in FIG. **1**B, according to an embodiment, the X-ray absorption layer **110** may include one or more diodes (e.g., p-i-n or p-n) formed by a first doped region **111**, one or more discrete regions **114** of a second doped region **113**. The second doped region **113** may be separated from the first doped region **111** by an optional the intrinsic region **112**. The discrete portions **114** are separated from one another by the first doped region **111** or the intrinsic region **112**. The first doped region **111** and the second doped region **113** have opposite types of doping (e.g., region **111** is p-type and region **113** is n-type, or region **111** is n-type and region **113** is p-type). In the example in FIG. **1**B, each of the discrete regions **114** of the second doped region **113** forms a diode with the first doped region **111** and the optional intrinsic region **112**. Namely, in the example in FIG. **1**B, the X-ray absorption layer **110** has a plurality of diodes having the first doped region **111** as a shared electrode. The first doped region **111** may also have discrete portions.

When an X-ray photon hits the X-ray absorption layer **110** including diodes, the X-ray photon may be absorbed and generate one or more charge carriers by a number of mechanisms. An X-ray photon may generate 10 to 100000 charge carriers. The charge carriers may drift to the electrodes of one of the diodes under an electric field. The field may be an external electric field. The electrical contact **119**B may include discrete portions each of which is in electrical contact with the discrete regions **114**. In an embodiment, the charge carriers may drift in directions such that the charge carriers generated by a single X-ray photon are not substantially shared by two different discrete regions **114** ("not substantially shared" here means less than 2%, less than 0.5%, less than 0.1%, or less than 0.01% of these charge carriers flow to a different one of the discrete regions **114** than the rest of the charge carriers). Charge Carriers generated by an X-ray photon incident around the footprint of one of these discrete regions **114** are not substantially shared with another of these discrete regions **114**. A pixel **150** associated with a discrete region **114** may be an area around the discrete region **114** in which substantially all (more than 98%, more than 99.5%, more than 99.9%, or more than 99.99% of) charge carriers generated by an X-ray photon incident therein flow to the discrete region **114**. Namely, less than 2%, less than 1%, less than 0.1%, or less than 0.01% of these charge carriers flow beyond the pixel.

As shown in an alternative detailed cross-sectional view of the detector **100** in FIG. **1**C, according to an embodiment, the X-ray absorption layer **110** may include a resistor of a semiconductor material such as, silicon, germanium, GaAs, CdTe, CdZnTe, or a combination thereof, but does not include a diode. The semiconductor may have a high mass attenuation coefficient for the X-ray energy of interest.

When an X-ray photon hits the X-ray absorption layer **110** including a resistor but not diodes, it may be absorbed and generate one or more charge carriers by a number of mechanisms. An X-ray photon may generate 10 to 100000 charge carriers. The charge carriers may drift to the electrical contacts **119**A and **119**B under an electric field. The field may be an external electric field. The electrical contact **119**B includes discrete portions. In an embodiment, the charge carriers may drift in directions such that the charge carriers generated by a single X-ray photon are not substantially shared by two different discrete portions of the electrical contact **119**B ("not substantially shared" here means less than 2%, less than 0.5%, less than 0.1%, or less than 0.01% of these charge carriers flow to a different one of the discrete portions than the rest of the charge carriers). Charge carriers generated by an X-ray photon incident around the footprint of one of these discrete portions of the electrical contact **119**B are not substantially shared with another of these discrete portions of the electrical contact **119**B. A pixel **150** associated with a discrete portion of the electrical contact **119**B may be an area around the discrete portion in which substantially all (more than 98%, more than 99.5%, more than 99.9% or more than 99.99% of) charge carriers generated by an X-ray photon incident therein flow to the discrete portion of the electrical contact **119**B. Namely, less than 2%, less than 0.5%, less than 0.1%, or less than 0.01% of these charge carriers flow beyond the pixel associated with the one discrete portion of the electrical contact **119**B.

The electronics layer **120** may include an electronic system **121** suitable for processing or interpreting signals generated by X-ray photons incident on the X-ray absorption layer **110**. The electronic system **121** may include an analog circuitry such as a filter network, amplifiers, integrators, and comparators, or a digital circuitry such as a microprocessors, and memory. The electronic system **121** may include components shared by the pixels or components dedicated to a single pixel. For example, the electronic system **121** may include an amplifier dedicated to each pixel and a microprocessor shared among all the pixels. The electronic system **121** may be electrically connected to the pixels by vias **131**. Space among the vias may be filled with a filler material **130**, which may increase the mechanical stability of the connection of the electronics layer **120** to the X-ray absorption layer **110**. Other bonding techniques are possible to connect the electronic system **121** to the pixels without using vias. The an electronic system **121** may be configured to count X-ray photons by the pixels or configured to measure the amounts of charge carriers accumulated at the pixels (e.g., by using an analog-to-digital converter (ADC) shared by the pixels).

FIG. **1**D schematically shows that the electrical contacts **119**A and **119**B may have structures extending into the X-ray absorption layer **110**. For example, the structures may be holes are drilled into the X-ray absorption layer **110** (e.g., by deep reactive-ion etching (DRIE) or laser and filled with a metal. The structures may form an Ohmic contact or a Schottky contact with the materials of the X-ray absorption layer **110**. The structures of the electrical contacts **119**A and the structures of the electrical contacts **119**B may form an interdigitate pattern but should not electrically short. These structures may help collecting charge carriers generated from an X-ray photon. The charge carriers only need to drift to one of these structures rather than the surfaces of the X-ray absorption layer **110**, thereby reducing the chance of recombination or trapping. Each of the structures of the electrical contacts **119**B may be spaced by a short distance (e.g., 20 μm, 50 μm or 100 μm) from the nearest one of the structures of the electrical contacts **119**A. The time for the charge carriers to be collected by these structures may be on the order of 0.1-1 ns.

FIG. **2** schematically shows that the detector **100** may have an array of pixels **150**. The array may be a rectangular array, a honeycomb array, a hexagonal array or any other suitable array. Each pixel **150** may be configured to detect an X-ray photon incident thereon, measure the energy of the X-ray photon, or both. For example, each pixel **150** may be configured to count numbers of X-ray photons incident thereon whose energy falls in a plurality of bins, within a period of time. All the pixels **150** may be configured to count the numbers of X-ray photons incident thereon within a plurality of bins of energy within the same period of time. Each pixel **150** may have its own analog-to-digital converter (ADC) configured to digitize an analog signal representing the energy of an incident X-ray photon into a digital signal. The ADC may have a resolution of 10 bits or higher. Each pixel **150** may be configured to measure its dark current, such as before or concurrently with each X-ray photon incident thereon. Each pixel **150** may be configured to deduct the contribution of the dark current from the energy of the X-ray photon incident thereon. The pixels **150** may be configured to operate in parallel. For example, when one pixel **150** measures an incident X-ray photon, another pixel **150** may be waiting for an X-ray photon to arrive. The pixels **150** may be but do not have to be individually addressable.

FIG. **3**A schematically shows the electronics layer **120** according to an embodiment. The electronic layer **120** comprises a substrate **122** having a first surface **124** and a second surface **128**. A "surface" as used herein is not necessarily exposed, but can be buried wholly or partially. The electronic layer **120** comprises one or more electric contacts **125** on the first surface **124**. The one or more electric contacts **125** may be configured to be electrically connected to one or more electrical contacts **119**B of the X-ray absorption layer **110**. The electronics system **121** may be in or on the substrate **122**. The electronic layer **120** comprises one or more vias **126** extending from the first surface **124** to the second surface **128**. The electronic layer **120** may comprise a redistribution layer (RDL) **123** on the second surface **128**. The RDL **123** may comprise one or more transmission lines **127**. The electronics system **121** is electrically connected to the electric contacts **125** and the transmission lines **127** through the vias **126**.

The substrate **122** may be a thinned substrate. For example, the substrate may have at thickness of 750 microns or less, 200 microns or less, 100 microns or less, 50 microns or less, 20 microns or less, or 5 microns or less. The substrate **122** may be a silicon substrate or a substrate or other suitable semiconductor or insulator. The substrate **122** may be produced by grinding a thicker substrate to a desired thickness.

The one or more electric contacts **125** may be a layer of metal or doped semiconductor. For example, the electric contacts **125** may be gold, copper, platinum, palladium, doped silicon, etc.

The vias **126** pass through the substrate **122** and electrically connect electrical components (e.g., the electrical contacts **125**) on the first surface **124** to electrical components (e.g., the RDL) on the second surface **128**. The vias

126 are sometimes referred to as "through-silicon vias" although they may be fabricated in substrates of materials other than silicon.

The RDL **123** may comprise one or more transmission lines **127**. The transmission lines **127** electrically connect electrical components (e.g., the vias **126**) in the substrate **122** to bonding pads at other locations on the substrate **122**. The transmission lines **127** may be electrically isolated from the substrate **122** except at certain vias **126** and certain bonding pads. The transmission lines **127** may be a material (e.g., Al) with small mass attenuation coefficient for the X-ray energy of interest. The RDL **123** may redistribute electrical connections to more convenient locations. The RDL **123** is especially useful when the detector **100** has a large number of pixels. If the detector **100** does not have a large number of pixels, the RDL **123** may be omitted and signals from the pixels may be routed on the first surface **124**.

FIG. **3**A further schematically shows bonding between the X-ray absorption layer **110** and the electronic layer **120** at the electrical contact **119**B and the electrical contacts **125**. The bonding may be by a suitable technique such as direct bonding or flip chip bonding.

Direct bonding is a wafer bonding process without any additional intermediate layers (e.g., solder bumps). The bonding process is based on chemical bonds between two surfaces. Direct bonding may be at elevated temperature but not necessarily so.

Flip chip bonding uses solder bumps **199** deposited onto contact pads (e.g., the electrical contact **119**B of the X-ray absorption layer **110** or the electrical contacts **125**). Either the X-ray absorption layer **110** or the electronic layer **120** is flipped over and the electrical contact **119**B of the X-ray absorption layer **110** are aligned to the electrical contacts **125**. The solder bumps **199** may be melted to solder the electrical contact **119**B and the electrical contacts **125** together. Any void space among the solder bumps **199** may be filled with an insulating material.

FIG. **3**B schematically shows the electronics layer **120** according to an embodiment. The electronics layer **120** shown in FIG. **3**B is different from the electronics layer **120** shown in FIG. **3**A in the following ways. The electronics system **121** is buried in the substrate **122**. The electronic layer **120** comprises one or more vias **126**A extending from the first surface **124** to the second surface **128**. The vias **126**A electrically connect the electrical contacts **125** to the transmission lines **127** in the RDL **123** on the second surface **128**. The electronic layer **120** further comprises one or more vias **126**B extending from the second surface **128** to the electronics system **121**. The vias **126**B electrically connect the transmission lines **127** to the electronics system **121**. The X-ray absorption layer **110** and the electronic layer **120** may also be bonded together (e.g., at the electrical contact **119**B and the electrical contacts **125**) by a suitable technique such as direct bonding or flip chip bonding.

FIG. **3**C schematically shows the electronics layer **120** according to an embodiment. The electronics layer **120** shown in FIG. **3**C is different from the electronics layer **120** shown in FIG. **3**A in the following ways. The electronics system **121** is buried in the substrate **122**. The electronic layer **120** does not comprise one or more electric contacts **125** on the first surface **124**. Instead, the substrate **122** including the buried electronics system **121** is bonded to the X-ray absorption layer **110** by direct bonding. Holes are formed in the substrate **123** and filled with metal to form the vias **126**A that electrically route the electrical contact **119**B to the second surface **128** and to form the vias **126**B that electrically route the electronics system **121** to the second surface **128**. The RDL **123** is then formed on the second surface **128** such that the transmission lines **127** electrically connect the vias **126**A and **126**B to complete the electrical connection from the electrical contact **119**B to the electronics system **121**. The X-ray absorption layer **110** may include multiple discrete chips. Each of the chips may be bonded to the electronic layer **120** individually or collectively. The X-ray absorption layer **110** including multiple discrete chips may help to accommodate the difference between the thermal expansion coefficients of the materials of the X-ray absorption layer **110** and the electronic layer **120**.

Signal from the electric contacts **125** may be read out column by column. For example, signal from one electric contact **125** may be stored in register in the electronics system **121** associated with it; the signal may be successively shifted from one column to the next, and eventually to other processing circuitry. If the RDL **123** exists, FIG. **4**A shows a top view of the RDL **123** in FIG. **3**A to illustrate the positions of the vias **125** and the transmission lines **127**, relative to the electric contacts **125** and the electronics system **121**, according to an embodiment. The electric contacts **125**, the electronics system **121** and the transmission lines **127** are shown in dotted lines because they are not directly visible in this view.

Signal from the electric contacts **125** may be read out pixel by pixel. For example, signal from one electric contact **125** may be stored in register in the electronics system **121** associated with it; the signal may be successively shifted from one electric contact **125** to the next, and eventually to other processing circuitry. If the RDL **123** exists, FIG. **4**B shows a top view of the RDL **123** in FIG. **3**A to illustrate the positions of the vias **125** and the transmission lines **127**, relative to the electric contacts **125** and the electronics system **121**, according to an embodiment. The electric contacts **125**, the electronics system **121** and the transmission lines **127** are shown in dotted lines because they are not directly visible in this view.

FIGS. **5**A-**5**D schematically show a flow of making the X-ray absorption layer **110**, according to an embodiment. FIG. **5**A schematically shows that the flow starts with a substrate **199** having a sacrificial layer **187**, an etch stop layer **188**, the first doped region **111**, the second doped region **113** and the intrinsic region **112**. The regions **111**, **112** and **113** are described above. The regions **112** and **113**, and the optional region **111** may function as the X-ray absorption layer **110**. The regions **111**, **112** and **113** may be layers epitaxially grown on the etch stop layer **188**. In one example, the sacrificial layer **187** is a GaAs wafer. The second doped region **113** is an N type GaAs epitaxial layer, which may have a thickness of about 5 microns. The intrinsic region **112** may be an intrinsic GaAs epitaxial layer with a thickness of less than 75 microns, less than 100 microns, less than 125 microns, or less than 200 microns. Alternatively, the intrinsic region **112** may be replaced with a lightly doped P type layer or a lightly doped N type layer. "Lightly doped" means that the energy levels of the dopants do not merge into an impurity band. In contrast, "heavily doped" means that the energy levels of the dopants merge into an impurity band. The first doped region **111** may be a heavily doped P type GaAs epitaxial layer with a thickness of 1 micron or more. In an embodiment, the first doped region **111** may be omitted.

FIG. **5**B schematically shows that the substrate **199** is attached to a substrate **900**. There may be a metal layer **930** to form electrical contact to the first doped region **111** if the first doped region **111** is present, or to the intrinsic region **112** if the first doped region **111** is absent.

The substrate **900** may be a material that has a low (e.g., <1000 $m^2/kg$) mass attenuation coefficient for the X-ray energy of interest. Examples of such a material may include silicon, silicon oxide, Al, Cr, Ti, etc. The substrate **900** does not have to be a single material. In one example, the substrate **900** may include a body of silicon and the surface contacting the X-ray absorption layer **110** may be a metal layer. In another example, the substrate **900** is a silicon wafer and the surface contacting the X-ray absorption layer **110** is heavily doped silicon. In another example, the substrate **900** is a glass wafer and the surface contacting the X-ray absorption layer **110** is a metal layer. The substrate **900** may have a sufficient strength to provide mechanical support to the X-ray absorption layer **110** during subsequent fabrication processes. The surface contacting the X-ray absorption layer **110** may be an electrically conductive material such as heavily doped silicon, Al, Cr, Ti, etc. The substrate **900** may be configured to be electrically connected to or serve as the electrical contacts **119**A of the X-ray absorption layer **110**.

FIG. **5**C schematically shows that the sacrificial layer **187** is removed by etching. Etching is stopped by the etch stop layer **188**. Even if the regions **111-113** may be of the same material as the sacrificial layer **187**, the etch stop layer **188** prevents etching of the regions **111-113** while allows etching of the sacrificial layer **187**. The etch stop layer **188** may be subsequently removed.

FIG. **5**D schematically shows that the discrete regions **114** and the electrical contacts **119**B may be formed partially from the second doped region **113**. The electronics layer **120** may then be attached to the chip **189** as described above.

FIGS. **6**A-**6**D schematically show a flow of making the X-ray absorption layer **110**, according to an embodiment. FIG. **6**A schematically shows that the flow may start with a substrate **199** having an intrinsic or lighted doped layer **184** and optionally the first doped region **111**. The region **111** is described above. In one example, the layer **184** is a GaAs wafer. The layer **184** may be intrinsic or lighted doped P type GaAs. The first doped region **111** may be a heavily doped P type GaAs epitaxial layer with a thickness of 1 micron or more. In an embodiment, the first doped region **111** may be omitted.

FIG. **6**B schematically shows that the chip **189** is attached to a substrate **900**. There may be a metal layer **930** to form electrical contact to the first doped region **111** if the first doped region **111** is present, or to the layer **184** if the first doped region **111** is absent.

The substrate **900** may be a material that has a low (e.g., <1000 $m^2/kg$) mass attenuation coefficient for the X-ray energy of interest. Examples of such a material may include silicon, silicon oxide, Al, Cr, Ti, etc. The substrate **900** does not have to be a single material. In one example, the substrate **900** may include body of silicon and the surface contacting the X-ray absorption layer **110** may be a metal layer. In another example, the substrate **900** is a silicon wafer and the surface contacting the X-ray absorption layer **110** is heavily doped silicon. In another example, the substrate **900** is a glass wafer and the surface contacting the X-ray absorption layer **110** is a metal layer. The substrate **900** may have a sufficient strength to provide mechanical support to the X-ray absorption layer **110** during subsequent fabrication processes. The surface contacting the X-ray absorption layer **110** may be an electrically conductive material such as heavily doped silicon, Al, Cr, Ti, etc. The substrate **900** may be configured to be electrically connected to or serve as the electrical contacts **119**A of the X-ray absorption layer **110**.

FIG. **6**C schematically shows that the layer **184** is thinned by a suitable method such as grinding, to a suitable thickness of less than 75 microns, less than 100 microns, less than 125 microns, or less than 200 microns.

FIG. **6**D schematically shows that the second doped region **113** may be disposed onto the layer **184**. The layer **184**, the second doped region **113**, and the optional first doped region **111** may function as the X-ray absorption layer **110**. The discrete regions **114** and the electrical contacts **119**B may be formed partially from the second doped region **113**. The electronics layer **120** may then be attached to the chip **189** as described above.

The X-ray absorption layer **110** as made by the flow of FIGS. **5**A-**5**D or the flow of FIGS. **6**A-**6**D may be bonded to the electronic layer **120** using a suitable method such that in FIG. **3**A, **3**B or **3**C.

FIG. **7**A shows that multiple chips may be bonded to a single electronic layer **120**, where each chip may include an X-ray absorption layer **110**, according to an embodiment. The smaller sizes of the chips relative to the electronic layer **120** may help accommodating the difference in thermal expansion coefficients of the chips and the electronic layer **120**. A ratio between the thermal expansion coefficient of the chips and the thermal expansion coefficient of the electronic layer **120** may be two or more. Bonding multiple chips onto a single electronic layer **120** may yield a large area detector.

FIG. **7**B shows that a single X-ray absorption layer **110** may be bonded to a single electronic layer **120**, according to an embodiment. FIG. **7**B is especially suitable for applications (e.g., intraoral X-ray applications) where the size of the detector does not have to be large.

FIG. **8** schematically shows a system comprising the semiconductor X-ray detector **100** described herein. The system may be used for medical imaging such as chest X-ray radiography, abdominal X-ray radiography, etc. The system comprises an X-ray source **1201**. X-ray emitted from the X-ray source **1201** penetrates an object **1202** (e.g., a human body part such as chest, limb, abdomen), is attenuated by different degrees by the internal structures of the object **1202** (e.g., bones, muscle, fat and organs, etc.), and is projected to the semiconductor X-ray detector **100**. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the X-ray.

FIG. **9** schematically shows a system comprising the semiconductor X-ray detector **100** described herein. The system may be used for medical imaging such as dental X-ray radiography. The system comprises an X-ray source **1301**. X-ray emitted from the X-ray source **1301** penetrates an object **1302** that is part of a mammal (e.g., human) mouth. The object **1302** may include a maxilla bone, a palate bone, a tooth, the mandible, or the tongue. The X-ray is attenuated by different degrees by the different structures of the object **1302** and is projected to the semiconductor X-ray detector **100**. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the X-ray. Teeth absorb X-ray more than dental caries, infections, periodontal ligament. The dosage of X-ray radiation received by a dental patient is typically small (around 0.150 mSv for a full mouth series).

FIG. **10** schematically shows a cargo scanning or non-intrusive inspection (NII) system comprising the semiconductor X-ray detector **100** described herein. The system may be used for inspecting and identifying goods in transportation systems such as shipping containers, vehicles, ships, luggage, etc. The system comprises an X-ray source **1401**. X-ray emitted from the X-ray source **1401** may backscatter from an object **1402** (e.g., shipping containers, vehicles, ships, etc.) and be projected to the semiconductor X-ray detector **100**. Different internal structures of the object **1402** may backscatter X-ray differently. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the backscattered X-ray and/or energies of the backscattered X-ray photons.

FIG. **11** schematically shows another cargo scanning or non-intrusive inspection (NH) system comprising the semiconductor X-ray detector **100** described herein. The system may be used for luggage screening at public transportation stations and airports. The system comprises an X-ray source **1501**. X-ray emitted from the X-ray source **1501** may penetrate a piece of luggage **1502**, be differently attenuated by the contents of the luggage, and projected to the semiconductor X-ray detector **100**. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the transmitted X-ray. The system may reveal contents of luggage and identify items forbidden on public transportation, such as firearms, narcotics, edged weapons, flammables.

FIG. **12** schematically shows a full-body scanner system comprising the semiconductor X-ray detector **100** described herein. The full-body scanner system may detect objects on a person's body for security screening purposes, without physically removing clothes or making physical contact. The full-body scanner system may be able to detect non-metal objects. The full-body scanner system comprises an X-ray source **1601**. X-ray emitted from the X-ray source **1601** may backscatter from a human **1602** being screened and objects thereon, and be projected to the semiconductor X-ray detector **100**. The objects and the human body may backscatter X-ray differently. The semiconductor X-ray detector **100** forms an image by detecting the intensity distribution of the backscattered X-ray. The semiconductor X-ray detector **100** and the X-ray source **1601** may be configured to scan the human in a linear or rotational direction.

FIG. **13** schematically shows an X-ray computed tomography (X-ray CT) system. The X-ray CT system uses computer-processed X-rays to produce tomographic images (virtual "slices") of specific areas of a scanned object. The tomographic images may be used for diagnostic and therapeutic purposes in various medical disciplines, or for flaw detection, failure analysis, metrology, assembly analysis and reverse engineering. The X-ray CT system comprises the semiconductor X-ray detector **100** described herein and an X-ray source **1701**. The semiconductor X-ray detector **100** and the X-ray source **1701** may be configured to rotate synchronously along one or more circular or spiral paths.

FIG. **14** schematically shows an electron microscope. The electron microscope comprises an electron source **1801** (also called an electron gun) that is configured to emit electrons. The electron source **1801** may have various emission mechanisms such as thermionic, photocathode, cold emission, or plasmas source. The emitted electrons pass through an electronic optical system **1803**, which may be configured to shape, accelerate, or focus the electrons. The electrons then reach a sample **1802** and an image detector may form an image therefrom. The electron microscope may comprise the semiconductor X-ray detector **100** described herein, for performing energy-dispersive X-ray spectroscopy (EDS). EDS is an analytical technique used for the elemental analysis or chemical characterization of a sample. When the electrons incident on a sample, they cause emission of characteristic X-rays from the sample. The incident electrons may excite an electron in an inner shell of an atom in the sample, ejecting it from the shell while creating an electron hole where the electron was. An electron from an outer, higher-energy shell then fills the hole, and the difference in energy between the higher-energy shell and the lower energy shell gray be released in the form of an X-ray. The number and energy of the X-rays emitted from the sample can be measured by the semiconductor X-ray detector **100**.

The semiconductor X-ray detector **100** described here may have other applications such as in an X-ray telescope, X-ray mammography, industrial X-ray defect detection, X-ray microscopy or microradiography, X-ray casting inspection, X-ray non-destructive testing, X-ray weld inspection, X-ray digital subtraction angiography, etc. It may be suitable to use this semiconductor X-ray detector **100** in place of a photographic plate, a photographic film, a PSP plate, an X-ray image intensifier, a scintillator, or another semiconductor X-ray detector.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

What is claimed is:

**1**. A method of making an apparatus suitable for detecting X-ray, the method comprising:
- obtaining a chip comprising an X-ray absorption layer;
- obtaining a substrate, wherein a surface of the substrate is electrically conductive;
- attaching the chip to the surface;
- thinning the X-ray absorption layer;
- forming an electrical contact on the X-ray absorption layer;
- bonding an electronics layer to the X-ray absorption layer such that the electrical contact on the X-ray absorption layer is electrically connected to an electrical contact of the electronics layer.

**2**. The method of claim **1**, wherein the substrate is not removed from the chip.

**3**. The method of claim **1**, wherein the substrate has a mass attenuation coefficient less than 1000 $m^2/kg$ for X-ray.

**4**. The method of claim **1**, wherein the substrate comprises silicon, glass, silicon oxide, Al, Cr, Ti, or a combination thereof.

**5**. The method of claim **1**, wherein thinning comprises reducing a thickness of the X-ray absorption chip to 200 microns or less, 100 microns or less, or 50 microns or less.

**6**. The method of claim **1**, wherein the X-ray absorption layer comprises GaAs.

**7**. The method of claim **6**, wherein the GaAs is not doped with chromium.

**8**. The method of claim **1**, wherein attaching the chip to the surface comprises depositing a layer of metal to the X-ray absorption layer.

**9**. The method of claim **1**, further comprising forming a diode in the X-ray absorption layer.

**10**. The method of claim **1**, wherein the electrical contact on the X-ray absorption layer comprises discrete portions.

**11**. The method of claim **1**, wherein the electric contact on the X-ray absorption layer comprises structures extending into the X-ray absorption layer.

**12**. A method of making an apparatus suitable for detecting X-ray, the method comprising:
- obtaining a chip comprising a sacrificial substrate and an X-ray absorption layer on the sacrificial substrate, wherein the X-ray absorption layer comprises a second

doped region, and wherein the second doped region and the sacrificial substrate are on a same side of the X-ray absorption layer;

obtaining a substrate, wherein a surface of the substrate is electrically conductive;

attaching the chip to the surface;

exposing the second doped region by removing the sacrificial substrate;

forming an electrical contact to the second doped region;

bonding an electronics layer to the X-ray absorption layer such that the electrical contact to the second doped region is electrically connected to an electrical contact of the electronics layer.

**13**. The method of claim **12**, wherein the chip further comprises an etch stop layer between the sacrificial substrate and the second doped region.

**14**. The method of claim **12**, wherein the chip further comprises an intrinsic region, wherein the intrinsic region and the sacrificial substrate sandwich the second doped region.

**15**. The method of claim **14**, wherein the intrinsic region has a thickness of less than 75 microns, less than 100 microns, less than 125 microns, or less than 200 microns.

**16**. The method of claim **12**, wherein the chip further comprises a lightly doped region, wherein the lightly doped region and the sacrificial substrate sandwich the second doped region.

**17**. The method of claim **16**, wherein the lightly doped region has a thickness of less than 75 microns, less than 100 microns, less than 125 microns, or less than 200 microns.

**18**. The method of claim **12**, wherein the second doped region is an epitaxial layer.

**19**. The method of claim **12**, wherein the chip further comprising a first doped region, wherein the second doped region is sandwiched between the first doped region and the sacrificial substrate.

**20**. The method of claim **19**, wherein the first doped region is heavily doped.

**21**. The method of claim **19**, wherein the first doped region is an epitaxial layer.

**22**. The method of claim **19**, wherein the first and second doped regions form a diode.

**23**. The method of claim **12**, wherein the electric contact to the second doped region comprises structures extending into the X-ray absorption layer.

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